**The behavioural preview effect with faces results from predictive processing
across the saccade**

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Abstract

The world around us appears stable and continuous despite saccadic eye movements. This apparent visual stability is achieved by trans-saccadic perception leading at the behavioural level to preview effects: Performance in processing a foveal stimulus is better if the stimulus remained unchanged (valid) compared to when it changed (invalid) during the saccade that brought it into focus. Trans-saccadic perception is known to predictively adapt to the statistics of the environment. Here, we asked whether the behavioural preview effect shows the same characteristics, employing a between-participants training design. Participants made saccades to faces which could change their orientation (upright/inverted) during the saccade. In addition, the post-saccadic face was slightly tilted and participants reported this tilt upon fixation. In a training phase, one group of participants conducted only invalid trials whereas another group conducted only valid trials. In a subsequent test phase with 50% valid and 50% invalid trials, we measured the preview effect. Invalid training eliminated the preview effect. With a mixed-model analysis, we could show how this training effect gradually declines in the course of the test phase. These results show that the behavioural preview effect adapts to the statistics of the environment suggesting that it results from predictive processes.

Introduction

We make about three saccadic eye-movements per second in everyday life. With these saccades, visual input changes drastically. We do not, however, notice these changes and we have the impression that the world around us is present in a stable and detailed fashion¹⁻³. Attempting to explain this apparent discrepancy, past

research revealed a number of interrelated features and feats of the visual system that contribute to the phenomenon of visual stability, such as saccadic suppression⁴, corollary discharge⁵, predictive remapping⁶⁻⁸, and trans-saccadic integration⁹⁻¹¹. Among these explanations, a central idea is that trans-saccadic processing involves a form of predictive processing^{3,12,13}. How exactly predictive processes contribute to stable visual perception is, however, yet not fully understood.

The set of mechanisms involved in trans-saccadic processing leads at the perceptual level to seamless visual experience and at the behavioural level to preview effects. Every time we make a saccade, we focus the high-resolution part of the retina, the fovea, on a certain spot in the visual field. Perception at this new location is, however, influenced by what we could see less clearly at that location before the saccade. If a stimulus changes during a saccade (invalid preview), processing the post-saccadic stimulus is worse as reflected in worse behavioural performance compared to when the stimulus did not change (valid preview)¹⁴⁻¹⁷. Buonocore and colleagues¹⁵, for instance, found worse performance in a gender discrimination task with human faces in a condition where the face changed from a scrambled to an intact face across the saccade compared to a condition where it did not change, i.e. where the intact face was already shown before the saccade. Preview effects are particularly well established in the domain of reading research¹⁸⁻²¹.

Considering that the behavioural preview effect involves a match between pre-saccadic and post-saccadic processing, while also considering that trans-saccadic processing is at least to some extent predictive, the question arises whether the behavioural preview effect can be conceived of as the result of a predictive process.

The idea here is that a change in visual input from before to after a saccade violates perceptual expectations¹⁴. Before a saccade is made, the visual system activates perceptual content which is likely to be encountered after the saccade. However, if not the expected input but something else is encountered (invalid preview), this new input triggers a prediction error and leads to worse and/or slower behavioural performance processing this new input. The basis for trans-saccadic predictions is presumably current peripheral visual input together with prior experience about how visual input changes from peripheral to foveal views. This idea is strongly supported by, for instance, Herwig and Schneider¹² who showed that consistent trans-saccadic changes in the spatial frequency of vertical gratings during an acquisition phase affected judgments about the spatial frequency of peripherally viewed gratings in a following test phase²². Similarly, Valsecchi and Gegenfurtner²³ provide evidence that peripherally viewed discs appear smaller (or larger) if they are replaced by a smaller (or larger) disc during a saccade directed towards them. These studies suggest that the visual system picks up on statistical regularities of how a stimulus changes from peripheral to foveal views leading eventually to altered peripheral perceptual experience. We wanted to know whether similar principles apply to the behavioural preview effect; in other words, we wanted to know whether the behavioural preview effect adapts to the statistical regularities of trans-saccadic changes. If that was the case, the behavioural preview effect could be considered as the result of predictive processing.

Previous research was somewhat inconclusive about whether the behavioural preview effect reflected predictive processing. So far, one study investigated the predictive nature of the preview effect with combined electroencephalography (EEG) and eye-tracking¹⁴. This study revealed several stages of pre- and post-saccadic

processing which were differentially affected by statistical regularities in trans-saccadic changes. Whereas pre-saccadic stages were influenced by the frequency of trans-saccadic changes, early post-saccadic stages were largely unaffected. Apart from these neurophysiological findings, the statistical evidence for whether the *behavioural* preview effect resulted from predictive processing was rather unclear (p-value around .03 and a Bayes factor suggesting the opposite result)¹⁴.

Considering the abundance of theories about predictive processing^{24–29}, it is important to clarify what kind of effects can be meaningfully accommodated in predictive processing frameworks in the first place. We are aware that the term prediction, even if limited to perceptual processing, encompasses a wide range of phenomena and can be conceptualized in different ways. Here, we conceive of prediction as a type of processing that adapts on a rather short time scale to certain statistical regularities concerning the frequency of events³⁰. Thus, demonstrating that the behavioural preview effect shows this feature means one step further in clarifying the scope of predictive processing in visual perception.

To answer the question of whether the trans-saccadic behavioural preview effect reflects predictive processes, we conducted a para-foveal preview experiment and employed a between-participants training design. In our gaze-contingent experiment, a pre-saccadic perifoveal face stimulus could change (invalid preview) or maintain (valid preview) orientation (upright or inverted) during the eye movement directed towards it. The task was to discriminate a tiny tilt (left or right) of the post-saccadic face, also called the target face. One group of participants conducted a training phase with only valid trials during which the upright or inverted preview face remained the same across the saccade. The other group conducted a training phase with only invalid trials where the upright or inverted preview face always changes its

orientation across the saccade. After the training phase, both groups of participants performed the same test phase with an equal frequency of valid and invalid trials. In this test phase, we measured the behavioural preview effect as the difference in post-saccadic face tilt discrimination performance between valid and invalid trials.

If the preview effect resulted from predictive processes, then the invalid training should result in a smaller preview effect compared to the valid training. The idea is that because of invalid training, trans-saccadic changes become more expected which increases performance in invalid conditions and reduces the difference in performance between valid and invalid trials. Moreover, if trans-saccadic perception flexibly adapts to the statistics of the environment, the expected influence of training is supposed to decay in the course of the test phase which contains the same number of valid and invalid trials for both training groups. We assessed this expected pattern of results by including trial number as a numeric predictor in a mixed model analysis. This setup provided the maximum temporal resolution to track changes in the behavioural preview effect across time, that is, at the single-trial level.

Methods

Participants

Data from 41 participants was collected. However, six participants performed with less than 60% average accuracy in the tilt discrimination task; therefore, they were excluded from the analysis. The remaining 35 participants had a mean age of 22.5 years, ranging from 18 to 41. Twenty-five of them were female, 29 right-handed, and 21 right-eye-dominant. All participants had normal or corrected-to-normal vision which was confirmed by an eyesight test using a Snellen chart. They

received a monetary reimbursement for their participation and gave written informed consent. The study was approved by the local ethics committee at the University of Trento and conducted in line with the Declaration of Helsinki.

Apparatus and stimuli

The experiment was programmed in Matlab (The Mathworks Inc.) with the Psychophysics toolbox^{31,32}. We used 16 face stimuli and their phase-scrambled counterparts from one of our previous studies (Experiment 2 of Huber-Huber et al., 2019, originals from the Nottingham face data base, <http://pics.stir.ac.uk/zips/nottingham.zip>). As in the previous study, a circular mask with a diameter of 2.88° ensured that internal facial features, such as eyes, eyebrows, nose, and mouth, were equally well represented in each image while the head shape was occluded. Low-level statistics of the faces and their phase-scrambled counterparts were controlled by equating the luminance profiles of all stimuli to the average profile across all face stimuli with the *histMatch* function of the SHINE toolbox³³. Face images were presented at 8° eccentricity to the left of a 0.5° by 0.5° fixation cross.

For technical reasons, the data had to be collected in two different rooms with different computer monitors and the same eye-tracker model in different mounting setups. The data of the first 21 of participants was recorded with a ViewPixx monitor with scanning LED backlight design (ViewPixx/EEG, VPX-VPX-2006A), with a symmetric pixel rise and fall time of 1 ms specifically design for vision research to replace cathode-ray tube monitors, running at 120 Hz screen refresh rate, whereas the remaining set of 16 participants was recorded with a cathode-ray tube monitor (Mitsubishi Diamond Pro 2070SB) at 85 Hz screen refresh rate (see below for implications on display timing). We consider both monitors equal enough in their

display properties in order that any differences are irrelevant for the current research purpose. Both sets of participants were recorded with Eyelink 1000 eye-trackers (SR Research, Ontario, Canada). The eye-tracker for the first set was in desktop mount mode and the eye-tracker for the second set was in tower mount mode. For both eye-trackers we used default settings for saccade detection (velocity threshold $35^\circ/\text{s}$, acceleration threshold $9500^\circ/\text{s}^2$). The eye-trackers were set to record the dominant eye which was determined by a hole-in-the-card test.

Procedure and design

Each trial started with a white fixation cross and a white placeholder ring of one pixel width presented on black background (illustrated in Figure 1). After the eye tracker detected stable gaze for 1000 ms, an upright (0°) or inverted (180°) preview face was presented. After another 500 ms of stable gaze, the fixation cross turned grey prompting the participant to look at the preview face. An online saccade detection algorithm detected the start of the saccade defined as two subsequent gaze samples more than 0.18° apart on screen. This procedure led to satisfactory results in the past¹⁴. Detecting a saccade triggered the presentation of a transient for 16.7 ms, corresponding to two frames on the scanning LED backlight monitor running at 120 Hz screen refresh rate for the first set of 21 participants, or 11.8 ms, corresponding to one frame on the CRT monitor running at 85 Hz screen refresh rate for the remaining 16 participants (cf. Apparatus and stimuli). The transient was the phase-scrambled version of the preview face and served to balance the amount of trans-saccadic change in visual input between valid and invalid preview conditions^{4,34}. After the transient, the same face image was presented again as target with the same (valid preview trial) or the opposite orientation (invalid preview trial). This design yielded the within-participant factors Preview (valid, invalid) and

Target Orientation (upright, inverted). In addition to its overall orientation (upright or inverted) the target face exhibited a small tilt (1.8°) either to the left or to the right. This tilt, whether left or right, had to be reported by manual button press on a USB computer keyboard. If there was a mistake in the trial procedure, e.g. participants moved their eyes before the 500 ms preview period had ended, the trial was restarted. The experimenter monitored online gaze detection during the experiment and initiated recalibration whenever progress stalled.

The experiment consisted of two parts, first a training and then a test phase. The training phase contained either only valid or only invalid trials (100% valid or 100% invalid). This pure training phase was followed by a mixed test phase containing the same number of valid and invalid trials (50% valid and 50% invalid). For each block of trials, upright and inverted target faces were equally distributed across the experiment. Each participant was assigned to either the valid or the invalid training condition depending on their arrival to the experiment. We paid, however, attention to replacing participants with very low performance within their group in order to balance the number of participants across groups. Finally, 17 participants had trained with valid and 18 participants with invalid trials. That means, in addition to the two within-participant factors Preview (valid, invalid) and Target Orientation (upright, inverted) the design contained a between-participants factor training (valid, invalid). Within each cell of the design the 16 individual face images repeated equally often. Each participant performed in total 1024 trials, 512 of them in the training and 512 in the test phase. Trials were grouped in blocks of 32 with optional breaks in between. Within the training and within the test phase the order of trials was randomized. For one participant the experiment had to be

214 restarted during the test phase and related to that reason an additional block of 32
215 test trials is available for this participant.

216
217 **Figure 1. Trial procedure and experimental design. A.** Example of a valid preview trial with an upright
218 target face. Stable gaze during the placeholder and preview periods made the fixation cross turn grey
219 which cued the participant to look at the face. During the saccade, a visual transient equated low-level
220 visual changes for valid and invalid trials. In most of the trials, the target face was presented before
221 fixation onset. It had a small tilt which had to be reported by button press upon fixation. Stimuli, target
222 face tilt and timeline are not drawn to scale. **B.** All possible within-participant conditions of Target
223 Orientation (upright, inverted) and Preview (valid, invalid). Only the target face was slightly tilted which
224 had to be reported by manual button press. **C.** Between-participants training setup. Each participant
225 performed a training phase with either only valid or only invalid trials. After the training phase, the
226 preview effect, i.e. difference in tilt discrimination performance between valid and invalid trials, was
227 measured in a separate test phase with an equal amount of valid and invalid trials.

Data analysis

We analysed manual response times, measured with respect to cue onset, and task errors of the test phase with mixed models (package lme4, version 1.1-21, Bates et al., 2013, in R, version 3.6.1, R Core Team, 2013). All data and analysis code to reproduce statistics and figures are provided online (see section Data Availability). Mixed-models provide the advantage of working with continuous numeric predictors, such as trial number, which enables us to estimate not only the effects of the experimental conditions but also how these effects change across time. The computed models were based on individual trial data and contained the random factor participant and the following fixed factors: the two-level within-participant factors Preview (invalid - valid) and Target Orientation (inverted - upright) as well as the two-level between-participants factor Training (invalid - valid). The contrasts of these factors were coded as successive difference contrasts (MASS package in R), which provides the advantage that the intercept of the model corresponds to the grand mean and the effect estimates for the factors correspond to the differences between conditions given the mean across the levels of the other factors. This scenario is comparable to traditional analysis of variance (Anova) procedures. To estimate the effect of change across time we included the numeric predictor trial number which was scaled (z-score) to be numerically in about the same range as the other factors, i.e. around -1 to 1. We also centred this numeric predictor on trial number one of the test phase which means that the effects of other factors will be estimated for the first trial of the test phase. This first trial was exactly our time point of main interest. We wanted to know whether the training phase influenced the preview effect without confounding contributions from the test phase

itself. Above all, these settings ensured that we finally also got to know how the preview effect then changed further in the course of the test phase.

In order to determine outlier trials, we filtered response times with a three median absolute deviation filter per participant, condition, and correctness of the response, which means that trials with a response time further away than three times the median absolute deviation from the participant-by-condition-by-correctness median were excluded. This approach is very robust and preferred to other approaches based e.g. on standard deviations³⁷. To ensure not only proper task behaviour but also proper target face fixation, we further limited the analysis to trials where the saccade end point was within 2.16° from the centre of the face stimulus.

To correct for the usual skewness of the response time distribution, we took the inverse and multiplied it by -1 to maintain the direction of effects. Values were back-transformed and converted to milliseconds for plotting. The analysis of response times was limited to trials with only correct responses. To model the continuous variable response times, we used a linear mixed model (command *lmer* of the lme4 package in R). In contrast, the binary variable task error was modelled with a multilevel logistic regression, i.e. a generalized linear model with a logit link function (command *glmer* of the lme4 package in R).

To avoid overestimation of the significance of effects, we included random slopes and aimed for the maximum model³⁸. We paid close attention, however, that all specified parameters could actually be estimated based on the given dataset, that is, we checked whether a model was singular or not³⁹. The maximum non-singular random slopes model, aka the maximum identified model, was compared to a null model without random slopes by means of a likelihood ratio test and Akaike's

Information Criterion (AIC) in order to see whether the random slopes did improve the fit to the data. This was always the case.

To determine the significance of fixed effects, we calculated profile confidence intervals of the maximum identified model. We consider an effect as significant if its 95% profile confidence interval excluded zero.

Results

Training changes the preview effect and this influence of training declines in the course of the test phase

As can be seen from Figure 2, the training manipulation had the expected effect. The valid training group showed a larger preview effect than the invalid training group, Preview x Training interaction $\beta = -0.070$, $SE = 0.018$, $t = -3.848$, $CI = [-0.105, -0.034]$. Note, that we obtained this estimate for the time point right after the training phase, for the first trial of the test phase. The complete set of fixed effect coefficients of the maximum identified model is shown in Figure 3 (for the model comparisons that led to this model, see Supplementary Table S1). Moreover, separate models for the two training groups confirmed that there was no evidence for a preview effect with invalid training, $\beta = 0.007$, $SE = 0.011$, $t = 0.607$, $CI = [-0.015, 0.028]$ (model 2b, see Supplementary Table S2), but a significant preview effect with valid training, $\beta = 0.076$, $SE = 0.015$, $t = 5.154$, $CI = [0.047, 0.105]$ (model 2a, see Supplementary Table S3).

Importantly, Figure 3 revealed that the preview effect was not only influenced by training but that this influence also varied over time as indicated by a Preview x Training x Trial Number interaction, $\beta = 0.028$, $SE = 0.014$, $t = 2.051$, $CI = [0.001, 0.055]$. This interaction is further illustrated in Figure 4 where the preview effect

corresponds to the difference between the solid (valid preview) and dashed (invalid preview) regression lines measured in the direction of the y-axis. As can be seen from this figure, the initial pattern of a preview effect for the valid training but not for the invalid training group (see also Figure 2) converged and equalled out with time. For the valid training group, the preview effect tended to decrease (with increasing values on the x-axis solid and dashed lines get closer), whereas for the invalid training group it tended to increased (if anything, with increasing values on the x-axis solid and dashed lines gain distance). In sum, this finding confirms that the preview effect was modulated by training and it adapted from trial to trial to the frequency of trans-saccadic changes.

Apart from the crucial and central Preview x Training x Trial Number interaction, the main effect of Target Orientation (inverted – upright) was clearly significant, $\beta = 0.037$, $SE = 0.010$, $t = 3.749$, $CI = [0.018, 0.056]$. Given its contrast of inverted face minus upright face, the positive β of this effect indicated that participants were faster with upright than with inverted targets. The Target Orientation effect also showed a borderline significant interaction with Trial Number, $\beta = 0.013$, $SE = 0.007$, $t = 1.866$, $CI = [-0.001, 0.027]$, suggesting because of the positive β , if anything, an increasing influence of target orientation on response times in the course of the test phase. This effect was, however, strictly speaking not significant and given its limited theoretical importance was not interpreted further.

Figure 2. Estimated marginal means from the maximum identified model on response time data (model 2). The preview effect, the difference between valid and invalid preview trials, depended on the training condition. In contrast to valid training, there was no evidence for a preview effect with invalid training (confirmed with separate models on only valid/invalid training data, see Models 2a and 2b in Supplementary Tables S2 and S3). Note that effect estimates were obtained for the first trial of the test phase. Error bars represent asymptotic confidence intervals.

Figure 3. Fixed effect coefficients of the maximum identified linear mixed model on response times (Model 2).

Figure 4. Response times showed an interaction of Training x Preview x Trial Number, which suggested that training with only valid trials resulted in a larger preview effect than training with only invalid trials particularly in the beginning of the test phase (Model 2). The preview effect then evolved in opposite directions for both training groups. Compared to the invalid training group, the preview effect in the valid training group declined. Each dot is one trial. Trial number was standardized and centred on the first trial of the test phase.

Task errors do not confound the results in response times

In contrast to the response time analysis above, task errors did not show any particular pattern of results across time of the test phase in connection with Training or Preview. Importantly, this result rules out any speed-accuracy trade-offs. The corresponding fixed effect coefficients of the maximum identified model are illustrated in Figure 5 (for the model comparisons that led to this model, see Supplementary Table S4). As can be seen from this figure, only Target Orientation seemed to show a borderline significant interaction with Trial Number, $\beta = -0.177$, $CI = [-0.359, 0.012]$. The negative β of this interaction suggested with time on task a decreasing influence of the target orientation on task errors. Considered in

348 combination with the corresponding effect in response times, which is if anything in
 349 the opposite direction, the target face orientation effect might actually not have
 350 changed much across time, but participants might have differently traded-off speed
 351 and accuracy across time. This effect is, however, not important to our main
 352 argument. Thus, task errors did not confound the crucial response time results
 353 reported above. Besides the questionable Target Orientation x Trial Number
 354 interaction, we found a very clear main effect of Target Orientation (inverted –
 355 upright), $\beta = 0.676$, $CI = [0.467, 0.890]$, showing that tilt discrimination
 356 performance was undoubtedly better with upright than with inverted faces, which is
 357 in line with the corresponding effect in response times.

358
 359 **Figure 5. Fixed effect coefficients of the maximum identified generalized linear model on task errors**
 360 **(Model 6).**

Discussion

In the present study, we investigated whether the behavioural preview effect can be conceived of as the result of a predictive process. In a between-participants training design, we manipulated the frequency of trans-saccadic changes with only valid or invalid trials in the training phase and an equal number of valid and invalid trials in the subsequent test phase. Mixed model analyses of response times and task errors with trial number as numeric predictor showed that the preview effect in response times, first, is affected by training. In line with our hypothesis, the invalid training group did not provide any evidence for a preview effect at the beginning of the test phase. In contrast, valid training showed a clear preview effect. The second important result from our study is that this initial difference in the preview effect due to training gradually converged and equalled during the test phase. Towards the end of the test phase the two groups showed more similar preview effects than at the beginning of the test phase. This result confirms the idea that the behavioural preview effect reflects a form of predictive processing that adapts flexibly on a small time scale to the statistics of the environment in terms of frequency of events.

Our findings corroborate and extend previous research on how trans-saccadic perception adapts to the statistics of the environment^{12,22,23}. Similar to, for instance, Herwig and Schneider¹², we found that repeated exposure to trans-saccadic changes during an acquisition phase influences trans-saccadic processing in a subsequent test phase. Whereas Herwig and Schneider showed that peripherally viewed objects appeared to have a higher spatial frequency if they always increased in spatial frequency during the saccade directed towards it, we provide evidence for the behavioural consequences of repeated exposure to trans-saccadic changes. Moreover, our results extend previous research about simple visual features like

spatial frequency¹², shape²², and size²³ to more complex visual input like human faces.

Reconsidering the results from previous research on the trans-saccadic preview effect with faces¹⁴, we might even speculate about the neural sources of the behavioural preview effect. Our previous EEG results suggested that in particular the pre-saccadic part of trans-saccadic processing is susceptible to the frequency of events and the statistics of trans-saccadic changes. Considering this finding, the training manipulation of the current experiment might have in particular affected this pre-saccadic stage. Possibly, the invalid training changed pre-saccadic processing in a way that finally led to a reduced influence of the preview face on post-saccadic target face processing.

Besides our main conclusion that the behavioural preview effect reflects a predictive process that flexibly adapts to the statistics of the environment³⁰, there is a second inter-related respect in which trans-saccadic perception can be considered as predictive. This second respect is whether trans-saccadic prediction also means that the visual system instantiates in some way, already before the saccade, the expected post-saccadic input¹². The results of the valid training condition fit in principle to this idea, because after valid training we found a clear preview effect which can be considered as the result of pre-saccadic activation of the expected post-saccadic input which leads to better performance if the post-saccadic input matches the expectation. However, this interpretation is more challenging for the result with the invalid training. If there was some pre-saccadic activation of the expected post-saccadic input, we should have found a reversed preview effect after invalid training, because after invalid training, the invalid condition should have contained expected post-saccadic input and therefore better

performance than the valid condition which contained unexpected post-saccadic input. Instead, invalid training only reduced the preview effect to statistical insignificance, but did not reverse it. This could mean that, during the invalid training, participants simply learnt to ignore the preview face instead of using it to predict post-saccadic input. Still, it is possible that more extensive training, e.g. longer duration of the training phase, will finally lead to a reversed preview effect. Based on the present data we can, however, conclude that the simple presence of a pre-saccadic preview stimulus does not necessarily trigger a pre-saccadic prediction about the post-saccadic target and that such a prediction depends on the context.

Apart from the crucial results about trans-saccadic perception, this dataset also shows a very clear face inversion effect in line with previous findings¹⁴. Tilt discrimination of upright target faces was better than that of inverted faces which is possibly related to the impaired recognition of inverted compared to upright faces⁴⁰. This effect, and the Target Orientation factor in the first place are, however, not relevant to trans-saccadic perception but a simple by-product of balancing upright and inverted faces across preview and target displays.

More generally, one interesting implication of the present results is that the proportion of valid trials within an experimental design may greatly affect the degree to which pre-saccadic visual input influences post-saccadic visual processing. The proportion of *valid preview* has varied extensively across the numerous studies of trans-saccadic perception conducted in various laboratories thus far. In some studies, valid trials were the majority within a block or even blocked together. Our results suggest this leads to the highest likelihood of finding a trans-saccadic effect. In contrast, many other studies have been designed in a way that valid predictions

about the post-saccadic stimulus are licensed only on a third or a fourth of trials, or even less^{9,10,15,16,19,41–45}. Typically, there is one *valid* match in spatial coordinators or in feature space, combined with two or more invalid conditions in which the location or visual features of the stimulus changes during the saccade in a way that is very unlikely in the real world. The current results suggest that experimental designs used in the past may have underestimated the magnitude, or even presence, of trans-saccadic prediction effects. Furthermore, our results raise the question of whether spatiotopic trans-saccadic effects may be more strongly influenced by the number of invalid conditions than retinotopic effects, because retinotopic effects are per definition *invalid* in at least their spatial aspect given our usually spatiotopically stable visual environment.

In sum, the present study, suggests that the behavioural preview effect reflects predictive processes that flexibly adapt to the statistics of the environment. Furthermore, our results suggest that the experience of visual stability is indeed based on predictive processing.

Data Availability

The raw data can be obtained from <https://doi.org/10.17605/OSF.IO/TY69K>. Analysis code in the form of an R markdown file is available from github https://github.com/chsquare/beh_pre_eff with the registered digital object identifier <https://doi.org/10.5281/zenodo.3746057>.

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Acknowledgements

This research was supported by an Erwin-Schrödinger Fellowship from the Austrian Science Fund (FWF, number J-4291) awarded to Christoph Huber-Huber.

Author Contributions

C.H.-H. and D.M. designed the experiment; C.H.-H. collected and analysed the data; C.H.-H. and D.M. interpreted the data; C.H.-H. drafted the manuscript; C.H.-H. and D.M. revised and approved the final version of the manuscript.

Competing Interests

The authors declare no competing interests.

Figure Legends

Figure 1

Trial procedure and experimental design. A. Example of a valid preview trial with an upright target face. Stable gaze during the placeholder and preview periods made the fixation cross turn grey which cued the participant to look at the face. During the saccade, a visual transient equated low-level visual changes for valid and

invalid trials. In most of the trials, the target face was presented before fixation onset. It had a small tilt which had to be reported by button press upon fixation. Stimuli, target face tilt and timeline are not drawn to scale. B. All possible within-participant conditions of Target Orientation (upright, inverted) and Preview (valid, invalid). Only the target face was slightly tilted which had to be reported by manual button press. C. Between-participants training setup. Each participant performed a training phase with either only valid or only invalid trials. After the training phase, the preview effect, i.e. difference in tilt discrimination performance between valid and invalid trials, was measured in a separate test phase with an equal amount of valid and invalid trials.

Figure 2

Estimated marginal means from the maximum identified model on response time data (model 2). The preview effect, the difference between valid and invalid preview trials, depended on the training condition. In contrast to valid training, there was no evidence for a preview effect with invalid training (confirmed with separate models on only valid/invalid training data, see Models 2a and 2b in Supplementary Tables S2 and S3). Note that effect estimates were obtained for the first trial of the test phase. Error bars represent asymptotic confidence intervals.

Figure 3

Fixed effect coefficients of the maximum identified linear mixed model on response times (Model 2).

Figure 4

Response times showed an interaction of Training x Preview x Trial Number, which suggested that training with only valid trials resulted in a larger preview effect

605 than training with only invalid trials particularly in the beginning of the test phase
606 (Model 2). The preview effect then evolved in opposite directions for both training
607 groups. Compared to the invalid training group, the preview effect in the valid
608 training group declined. Each dot is one trial. Trial number was standardized and
609 centred on the first trial of the test phase.

610 **Figure 5**

611 Fixed effect coefficients of the maximum identified generalized linear model on
612 task errors (Model 6).

613