Looking at choice blindness: Evidence from gaze patterns and pupil dilation

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In a choice blindness task, participants often do not notice when their choices and outcomes are mismatched, and they tend to endorse the outcome that they initially rejected. Previous studies on choice blindness have mainly relied on participants' subjective reports to assess their detection of the mismatch. In this study, we measured participants' response times, pupil responses and eye-movements during the false feedback phase of a computerized choice blindness task. We found significant differences in all measures between trials where participants detected and corrected the mismatch and trials where they accepted the mismatch or where no mismatch occurred. Trials where participants accepted the mismatched outcome as their own showed similar eye-movement patterns to control trials, but longer response times and increased pupil responses, possibly indicating effortful rationalization. Together the patterns of results allow us to reject notions that participants are aware of, but fail to report, the manipulations during accepted manipulated trials.

Keywords: decision making, self-knowledge, choice blindness, pupil dilation, eye-tracking, process tracing

In everyday life, when making choices, we expect that the chosen option will be given to us once we have selected one option over another. If we don't receive the option selected, our common sense notion of decision making implies that we expect ourselves to notice and protest the matter. Choice blindness is the finding that this intuition does not universally hold, as it is possible to experimentally induce mismatches between choices and their outcomes that participants failed to detect (P. Johansson et al., 2005). In other words, a person may indicate a preference for option A but then accept receiving option B. This paper takes a process tracing approach to investigate what happens when people are confronted with mismatches between choices and outcomes, both when they accept or correct those mismatches.

In a choice blindness experiment, participants make preferential choices between options. On manipulated trials, using experimental subterfuge, participants receive false feedback about their choice. In the original work on choice blindness participants chose between pairs of faces which they preferred (P. Johansson et al., 2005), but the effect has since been both replicated (P. Johansson et al., 2014; Luo & Yu, 2017; Sauerland et al., 2016; Taya et al., 2014) and extended to a variety of choice domains including moral (Hall et al., 2012; Vranka & Bahník, 2016) and political attitudes (Hall et al., 2013; Strandberg et al., 2020; Strandberg et al., 2018), financial decisions (McLaughlin & Somerville, 2013), risk preferences (Kusev et al., 2022), food and drink preferences (Cheung et al., 2016), eye-witness lineup decisions (Cochran et al., 2016; Sagana et al., 2014a), as well as, decisions made in groups (Pärnamets, von Zimmermann, et al., 2020). In these experiments, participants will accept an outcome opposite to their intended in between a third to a full eighty percent of trials. When confronted with false feedback about their choices and accepting the manipulated outcome as real, participants confabulate reasons for the choice they didn't make. These confabulations are difficult to distinguish linguistically from what participants say when explaining their actual choices (P. Johansson et al., 2005; P. Johansson et al., 2006), indicating the psychological reality of the accepted false feedback to the participant. Furthermore, ac-

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cepting the false feedback in a choice blindness experiment has downstream consequences on later cognition. For example, participants exhibit false memories about what they originally chose following manipulations (Pärnamets et al., 2015), and when asked to make a second choice between the same options where the outcome was manipulated, participants are more likely to select the believed-to-be chosen option (P. Johansson et al., 2014; Luo & Yu, 2017; Taya et al., 2014). Such preference change can linger for up to a week for political attitudes (Strandberg et al., 2018). Choice blindness is thus a highly robust and replicable experimental phenomenon.

Despite this wealth of findings, it is still relatively unknown what happens when participants are given false feedback about their choices. While the subjective reports in choice blindness experiments clearly show that participants are saying that they believe their manipulated choice is their own, lingering doubts may still be had. In particular, is it possible that participants are covertly noticing the manipulation but choosing not to report this to acquiesce the experimenters; i.e. could choice blindness be due to some form of elaborate demand effect Jack, 2013; J. Moore and Haggard, 2006? Or could it be that the participants fail to detect the manipulation because they did not properly engage with the task at hand - not paying enough attention to the presentation of the false feedback? Also, even if few differences were found when comparing the verbal reports when participants explained a choice they did make and one they merely think they made P. Johansson et al., 2005; P. Johansson et al., 2006, could there be other measures that may separate these two types of trials? Given the implication of choice blindness for our common-sense notion of decision making, our understanding of rationalization in cognition (Cushman, 2020), and its incompatibility with a naïve conception of intentions in goal-directed actions (Hall et al., 2006; Lind et al., 2014b), a better understanding of the processes underpinning the choice blindness effect is necessitated. Here we begin to address this challenge in an attempt to map what happens when participants are confronted with false feedback about their choices.

To do so we adopt a process tracing approach common in decision research (Schulte-Mecklenbeck et al., 2017; Svenson, 1979). In process tracing researchers make time-dependent, pre-decisional observations in order to make better inferences about the cognitive process that led to that decision. Methods employed can range from verbal protocols (Svenson, 1979), skin conductance measures (Crone et al., 2004), eye-tracking (Glaholt & Reingold, 2011; Pärnamets et al., 2016), to neural measurements (Konovalov & Ruff, 2022). In a choice blindness task, there are two relevant decision points. The first is the original choice between the two faces. The second is how to respond when asked why the chosen face was preferred. When contemplating this second choice, the participants have the option to indicate that they actually preferred the other face, a response we categorise as correction of the manipulation. It is the time period leading up to this second decisions we investigate in this paper, looking at the participants' response times, pupil dilation and gaze patterns.

The time it takes to perform a task has long been linked to its difficulty (Hick, 1952). Difficulty in choice tasks is thought to relate to the relative discriminability of options and to the number of options under consideration. In general, the more discriminable options are, and the fewer they are, the faster choices can be made, although the relation between choices and response times also involves a trade-off between speed and accuracy (Bogacz et al., 2010; Ratcliff, 1978). Therefore, response times are highly suitable aggregate measures to capture how participants react to false feedback. If decisions to accept the false feedback are faster than to correct it, this might indicate fast errors on behalf of participants. If instead decisions to accept are slower than corrections, it can indicate high discriminability of the corrected manipulation. Response times can therefore provide initial evidence for how reactions to false feedback are formed that can be constrained by the pupil and gaze measures also collected.

Pupil dilation is a non-invasive measure of human cognitive processing (Hess & Polt, 1964; Joshi & Gold, 2020; Laeng et al., 2012). Pupillary constriction and dilation under isoluminant conditions is regulated by norepinephrine release from the locus coeruleus (Joshi et al., 2016), a region thought to exert brain wide modulation of cognition (Aston-Jones & Cohen, 2005). Experimental work has linked changes in pupil size with increased cognitive effort (Hess & Polt, 1964; Steinhauer et al., 2004) and to the experience of unexpected outcomes in decision tasks (Preuschoff et al., 2011). More broadly past findings can be interpreted such that pupil dilation indexes attention to salient stimuli or general task engagement (Aston-Jones & Cohen, 2005; Hoeks & Levelt, 1993). Additionally, the pupil signal evolves over time with a latency of around 0.33s to 1.25s (Chapman et al., 1999), although some work has shown that that the pupil signal can also index cognitive response on very brief timescales of around 100ms (Zylberberg et al., 2012). Together, these features make the pupil signal highly suitable for investigation in relation to the presentation of false feedback during a choice blindness task, as the manipulation presents both a surprising stimulus and, consequently, a situation demanding cognitive effort to resolve.

During natural viewing, attention is highly yoked to shifts in gaze direction (Deubel & Schneider, 1996), meaning that by recording eye-movements inferences can be made about what participants are currently attending to. Such attention can reflect unfolding cognitive processing. For example, by examining the pattern and time course of eye gaze when par-

ticipants view visually presented scenes and simultaneously listen to spoken descriptions of those scenes, it is possible to reveal aspects of both linguistic and higher-order processing (Ferguson & Breheny, 2011; Tanenhaus et al., 1995). Eye gaze not only reflects ongoing cognitive processes, but may also actively aid them. For example, by directing fixations towards critical portions of a visual insight problem, participants' performance is increased (Grant & Spivey, 2003). Similarly, recall can be aided by looking to where information has previously been presented (R. Johansson & Johansson, 2014) and accuracy in categorization tasks can be improved by cueing gaze (Hartendorp et al., 2013). Thus, quantifying gaze patterns is a tool well suited to measure possible processing differences and similarities in response to the false feedback.

Overview of study

In this paper we present the results from a computerized choice blindness experiment, in which participants made choices between pairs of faces based on attractiveness. Following each choice and a confidence rating, participants were presented with a feedback screen where they were shown the face they chose. On some - manipulated - trials participants were given false feedback and shown the opposite face to their chosen one. Participants were tasked to select which facial feature was most important in determining their choice by button press, but were also given an option to indicate that the face was not their preferred one indicating a correction of the false feedback. During this feedback screen, participants' eye-movements and pupil dilation were monitored and their response times recorded.

In a typical choice blindness task participants are presented with their choice - a card - by the experimenter and asked to give reasons for that choice while holding that card and looking at it (P. Johansson et al., 2005). Such a design makes eye-movements difficult to study. Here we instead opted for a design where the cards, chosen and non-chosen, as well as response options, are all visually present during the false feedback portion of the task (see Fig. 1). By creating portions of the screen corresponding to accepting the false feedback and a portion corresponding to correct it, participants can anchor their unfolding response to visually available portions of the screen. This design allows us to unobtrusively monitor how participants react to and interact with false feedback leading up to their response to it.

Throughout the paper we report contrasts between different trial-types depending on what feedback participants received about their choices and their reactions to it. Control trials are the trials in which participants received veridical feedback about their choice and set baseline responses for the measures we study and the task at hand. Accepted trials are trials when participants failed to notice and correct the choice blindness manipulation. We call trials where participants notice the false feedback for corrected trials, and divide these into first and all later corrections. We expected participants responses on accepted trials to be relatively similar to control trials, as participants during these trials inspect their chosen face and select a reason for having done so. By contrast, we expected corrected trials to differ considerably from both control and accepted trials, reflecting the radically different process of noticing the false feedback and formulating a response to it.

Method

Participants

We recruited 80 participants, of these, four participants failed to calibrate to the eye-tracker leaving a total of 76 participants (44 women) with an average age of 26.1 (SD = 9.3). Participants were recruited through announcements on noticeboards at Lund University libraries, and participation was in exchange for a cinema voucher (approximate value 120 SEK). Research was conducted in according to the Declaration of Helsinki and was approved by the regional ethics board of Lund University (D.nr. 2009/105).

Equipment & stimuli

Both male and female faces were used, but in same gender pairs. Face pairs were selected from a larger database (P. Johansson et al., 2005), so that one face in the pair didn't dominate the other during pilot tests (maximum of 3:1 choice ratio). Face pairs were presented in a randomized order during each experiment, ensuring that any face pair was eligible for choice blindness manipulation. These design choices were made to ensure that rejection rates of the manipulation were high enough to allow comparisons between accepted and rejected trials.

Eye tracking was conducted using an SensoMotoric Instruments HiSpeed system recording at 500Hz and eye data was logged with the iView X 2.7.8 software. Calibration of each participants' gaze data was performed using a thirteen point calibration routine plus validation. Calibration points with an error over 0.5° were never accepted and rendered recalibration.

The experiment was programmed in and presented with help of PsychoPhysics Toolbox 3 (Kleiner, 2007) for MATLAB on a 19" screen running at a resolution of 1280 x 1024 pixels.

Experimental procedure

When entering the lab we informed participants that they were going to take part in a face preference task and we gave them an introduction to the eye-tracker. Participants were given onscreen instructions followed by the eye-tracker calibration.

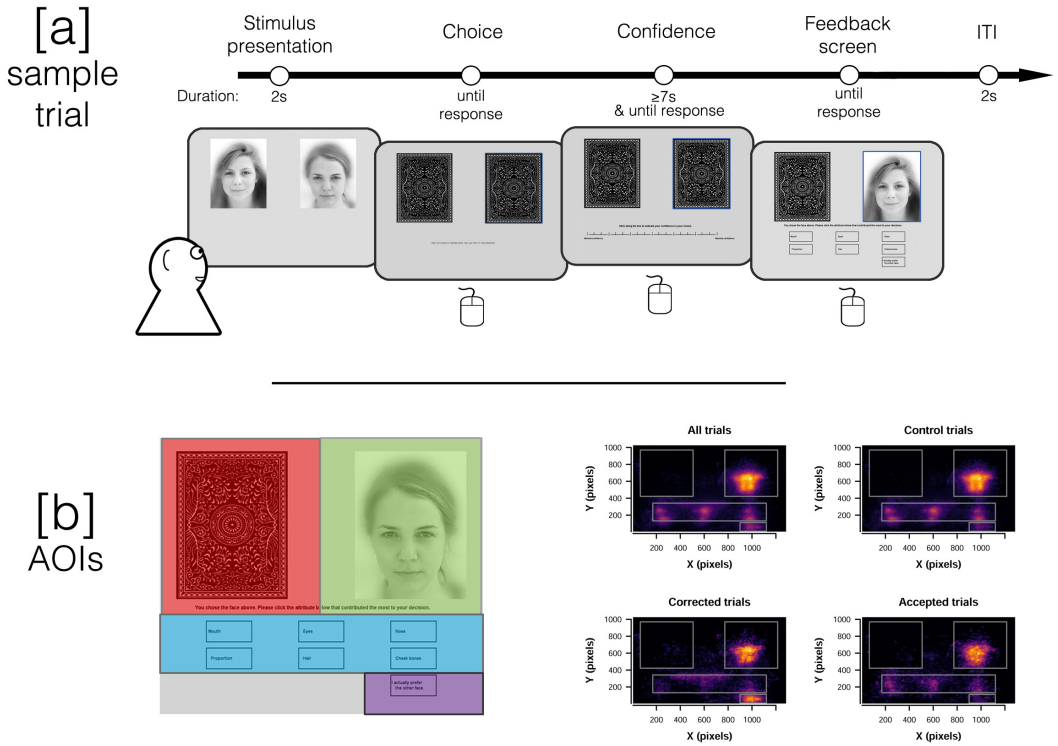

Figure 1

Overview of experimental procedure. ***(a) Sample trial.*** *Participants viewed the presented faces for 2s. Once the cards had turned over, the preferred face was selected by clicking the card-back where it had been shown. Selected choices were highlighted. Following choice participants' confidence in their choice was asked, and this screen was shown until response or at least 7s had passed. Finally, the card participants had selected turned over. During control trials the selected face was represented. During manipulated trials (pictured) the non-chosen face was presented. Participants were asked to select which of six presented facial features represented the reason for their choice. A seventh option (bottom right) was also always present which read "I actually prefer the other face". On manipulated trials, if participants clicked this button the manipulation was regarded as corrected, otherwise as accepted. Once participants had clicked a button a 2s interstimulus interval ensued before the next trial commenced.* ***(b) AOIs.*** *Left panel. For the analysis of direction of eye gaze four AOIs were defined – one for the card (red), one for the presented face (green), one for the facial feature buttons (blue) and one for the 'other preference' button (purple). The right panel plots heatmap of all recorded gaze samples to the feedback screen. Gaze samples to the face and card AOI have been reverse-coded for those trials where the chosen face was the left option. Right panel Heatmaps showing the overall distribution of gaze samples to the different AOIs for all trials and split by control, corrected or accepted trial status.*

The experiment consisted of 36 trials. At the start of each trial, two playing cards were displayed face down (see Fig. 1). After 0.5 seconds, the cards rotated 180 degrees and revealed two faces. The faces were fully displayed for 2 seconds, after which the cards would rotate back. Participants selected the face they preferred using the mouse. The participants' selection was marked by a colored rectangle surrounding the card of their choice. Following selection participants were asked to estimate their confidence in the choice on a 1 to 7 continuous scale by clicking along the scale using the mouse. Participants were then asked to wait so that the waiting time plus their response time to the confidence scale would add up to a total of 7 seconds. Once the occlusion time had passed the chosen card would rotate so that the face would be shown a second time. Participants were asked, during this feedback screen, to select why they had chosen that face from a list of six facial features. The wording was as follows: "You chose the face above. Why did you choose this face?" The features given to participants were "mouth", "eyes", "nose", "proportion", "skin", and "shape".

In addition to these six options, participants were also given a seventh option which read "I actually prefer the other face". Participants selected one option by clicking on it. There was a 2 second pause before the next trial commenced.

Choice blindness manipulation

For 8 of the 36 trials the chosen face was not displayed during the feedback screen, instead the non-chosen face was displayed. We refer to such trials with *false feedback* about the participants' choice as *manipulated trials* and the remaining trials with veridical feedback as non-manipulated, *control* trials.

We operationalised rejection of the false feedback as when participants clicked the "I actually prefer the other face" button (hereafter: 'other preference' button). Such trials are referred to as *corrected* trials and manipulated trials where participants clicked any of the facial features are referred to as *accepted* trials. A pilot study was conducted prior to running the present study testing this operationalisation. We found that participants rarely clicked 'other preference' apart from on manipulated trials, and post-test interview were used to confirm that participants use of the 'other preference' button conformed to them not accepting the presented face as their own.

The first six trials during each experimental session were never manipulated. Following those first trials, manipulated and control trials were presented in pseudo-randomly with the condition that two manipulated trials never immediately followed one another.

Analysis

Pupil signal processing

Continuous pupil data was extracted from each participant and trial. Eye blink artefacts were removed by first removing all points that exceeded 3 standard deviations and then linearly interpolating over all missing data points. The pupil signal was smoothed using a low-pass filter at 5.4 Hz. Finally, the pupil signal was converted to z-scores on a by-trial basis using data from the full trial. The resulting z-scores during the analyzed false feedback portion of the trial thus reflect differences relative to the participants pupil signal throughout the trial.

Gaze data processing

To analyze the gaze data we defined four areas of interest on the feedback screen (see Fig. 1b) and classified all gaze points as falling in one of these four areas or outside (coded as *NA*). We defined one area to be the presented face, the second was the card which was not turned up, the third covered the response buttons representing different facial features and, lastly, the fourth was the 'other preference' button.

We also performed a recurrence quantification analysis (RQA) of the fixations during the feedback portion of each trial to investigate the temporal structure of fixations (Anderson et al., 2013). Fixations were counted as recurring if they fell within 49 pixels of each other – equivalent to 1.5 degrees of visual angle (Anderson et al., 2013). The number of recurrent fixations (REC) is reported as a proportion. We calculated two measures associated with RQA from the recurrent fixations by first constructing an $m \times m$ square matrix recurrence plot, where m is the number of fixations. Recurrent fixations are plot as a dot, for example in coordinates (i, j) if fixation i and fixation j are recurrent. The first measure we calculated, determinism (DET), counts diagonal sequences in the recurrence plot. This measure, determinism represents recurring sequences of fixations, i.e. inspecting several portions of the screen in the same pattern at one time and then at another time. The second measure we calculated, laminarity (LAM), counts horizontal and vertical sequences in the recurrence plot. Laminarity represents multiple fixations to the same region, for example during a closer inspection of an element of the display. The DET and LAM measures were calculated using a minimum length of two subsequent fixations. All measures reported are percentages of recurrent fixations.

Statistical analysis

Analyses were performed in the R statistical language using the *brms* package (Bürkner, 2017). We analyzed the data using Bayesian multi-level regression models. All analyses were performed using maximal varying-effects structures, including varying intercepts and slopes grouped by both participant ID and by stimulus ID, as well as, correlations between group varying intercepts and slopes. All model specifications, including priors, are reported in the Supplementary Materials.

Analyses are based on comparing the four trial-types. For all models, except the growth curve models (details below), trial type was input as a four-level nominal variable with factor levels coded using orthonormal contrasts (Lüdecke et al., 2022; Rouder et al., 2012). This coding ensured that priors were equal for all contrasts when comparing trial-types, which is necessary for the interpretability of the Savage-Dickey Bayes Factors. Using the resulting posterior parameter estimates, contrasts between trial-types were computed and are reported. For all analyses we report the computed contrast, its 95% Highest Density Interval (HDI) and associated Savage-Dickey Bayes Factor. HDI was calculated using the *HDInterval* package (Meredith & Kruschke, 2020). To quantify relative evidence for an effect we report Savage-Dickey Bayes Factors, which are calculated as the density ratio between the posterior and prior distributions of a parameter evaluated at 0 (null). We interpret Bayes Factors >= 3 as weak evidence for an effect and >= 10 as strong evidence for

an effect. Since our analyses utilize weakly regularizing zero centered priors with the highest prior density at the point null we interpret Bayes Factors < 1 as weak evidence for null and <= .33 as strong evidence for the null.

To analyze gaze and pupil trajectories we employ growth curve analysis (Mirman, 2017). All growth curve models modelled the first 3s of each trial, downsampled to 30 timepoints to achieve reasonable running times for the models. Time was modeled using three orthogonal time terms (i.e., linear, quadratic and cubic). Trial-types were entered into the models using separate dummy terms which were allowed to interact with orthogonal time terms. No intercept term was included, ensuring contrasts between model terms would have equal priors. To compute when in time different trial-types differed respect to the dependent variable (gaze trajectory or pupil dilation), posterior trajectories were generated from the fitted model. These were compared for overlap using a stringent threshold ($P < .001$).

Data and code availability

Experimental data and analysis code are available from the Open Science Framework https://osf.io/pf325/?view_only=b6f8f862b8904cbd8f797773d77f87c2

Results

Correction rates

Of the total of 608 manipulations performed, 394 (64.8%) were corrected, leaving 214 (35.2%) as accepted. Each participant detected on average 5.2 (SD = 2.5) trials.

We examined if confidence, choice response times or their interaction predicted subsequent correction on manipulated trials using a multi-level logistic regression model. The model indicated weak evidence that choices that were made with higher confidence were also more likely to be corrected (b = 0.34, CrI = [0.05, 0.65], BF_{10} = 3.9). We found no effects on likelihood of correction involving choice response times (b = -0.078, CrI = [-0.40, 0.24], BF_{10} = 0.36) or their interaction with choice confidence (b = 0.072, CrI = [-0.26, 0.46], BF_{10} = 0.37).

Response times to feedback

Response times to the feedback portion of the trial, where the choice blindness manipulation occurs, provides a first indicator of processing differences between trial types. During control trials participants responded to the feedback screen on average after 5.6s (SD = 4.2), when accepting the manipulation average response times longer (M = 6.6s, SD = 5.2). Splitting corrected trials into first corrections and later corrections revealed a divergent pattern: first corrections were longest of all trial-types (M = 9.32s, SD = 7.0) while later corrections were fastest (M = 4.0s, SD = 3.9). We used a shifted-lognormal regression model to test if the patterns of differences in response times differed statistically. Computing contrasts between all four trial-types indicated that all comparisons were statistically reliable. Response times when making the first correction were longer compared to later corrections (b = 0.87, CrI = [0.65, 1.08], $BF_{10} > 10^4$), accepted trials (b = 0.28, CrI = [0.061, 0.51], BF_{10} = 7.7) and control trials (b = 0.53, CrI = [0.34, 0.72], $BF_{10} > 10^4$). Later corrections were faster than accepted trials (b = -0.58, CrI = [-0.77, -0.40], $BF_{10} > 10^4$) as well as control trials (b = -0.34, CrI = [-0.48, -0.19], $BF_{10} > 10^4$), while accepted trials were slower compared to control trials (b = 0.24, CrI = [0.096, 0.39], BF_{10} = 56.4; see also Supplementary Table 1). The results indicate that making a first correction is time consuming for participants, but subsequent corrections are relatively fast and effortless responses.

Pupil dilation

Average z-scored pupil dilation over the course of participants responses to the feedback screen was largest during first correction trials (M = 1.31, SD = 0.74) and later correction trials (M = 0.80, SD = 0.81), followed by accepted trials (M = 0.47, SD = 0.77) and smallest for control trials (M = 0.21, SD = 0.72). Contrasts computed from a regression model with condition as predictor revealed strong evidence for differences between all four trial-types. Participants' pupils were more dilated when correcting the false feedback the first time compared to later corrections (b = 0.41, CrI = [0.24, 0.58], $BF_{10} > 10^4$), accepted trials (b = 0.75, CrI = [0.58, 0.93], $BF_{10} > 10^4$) and control trials (b = 1.00, CrI = [0.84, 1.16], $BF_{10} > 10^4$). Likewise participants' pupils were more dilated during later corrected trials compared to both accepted (b = 0.40, CrI = [0.19, 0.48], $BF_{10} > 10^4$) and control (b = 0.59, CrI = [0.47, 0.70], $BF_{10} > 10^4$) trials. Finally, participants' pupils were also more dilated during accepted trials compared to control trials (b = 0.25, CrI = [0.14, 0.36], BF_{10} = 628; see also Supplementary Table 2).

We next examined the time course of pupil dilation. We extracted the first 3s of data for each trial time locked at the onset of false feedback. To quantify the growth trajectories we used cubic orthogonal time terms. We quantify the results both using model predictions and by contrasting the time terms by trial type. We compared the full posterior model predictions for each trial-type against the others using a threshold of $P < .001$. This analysis revealed that differences between trial-types emerged early, particularly between first corrected trials and the other trials, and that these differences were sustained during the period of consideration (see Figure 2 B). We next computed contrasts on the orthogonal time terms by trial-type. The differences revealed in the previous analysis are accounted for primarily by contrasts in the linear growth components of the model but not in the overall curvature of the pupil response (see Table 1; see also Supplementary Tables 3-4).

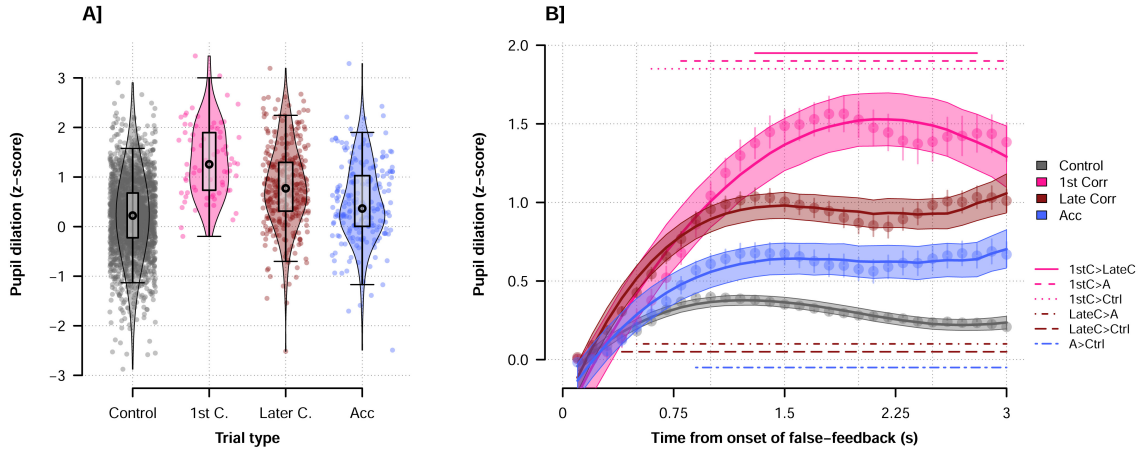

Figure 2

(A] Average pupil dilation. *Violin plots of participants' average pupil dilation during each trial when viewing the feedback screen. Dilation is z-scored relative to the onset of the feedback screen. Boxplots depict the median, first and third quartiles and 1.5*interquartile range.* ***B] Time course of pupil dilation.*** *Average time course of pupil dilation (z-scored) to the first 3s of viewing the feedback screen. Dots represent observed data and error bars their standard error. Lines are posterior predictions from Bayesian growth curve model and the shaded region represents the 95% credible interval.*

Recurrence quantification analysis

We next analyzed patterns of recurrence, computing two metrics on the recurrent fixations - determinism (DET) and laminarity (LAM).

Determinism (DET)

We first considered determinism (DET) which captures repetitions of fixation sequences. This measure was heavily zero-inflated and we report the descriptive results both overall and conditional on a deterministic sequence being present in a trial. Overall, for control trials, 6.7% (*SD* = 12.7) of recurrent fixations formed deterministic patterns, while for accepted trials this number was 7.9% (*SD* = 11.3). For first corrected trials determinism was 12.5% (*SD* = 18.6) and for later corrected trials it was 8.2% (*17.6*). Conditional on a deterministic sequence being present, for control trials proportion recurrent fixations forming deterministic patterns was 18.6% (*SD* = 12.9), for accepted trials 17.8% (*SD* = 12.9), for first corrections 19.7% (*SD* = 15.8), and for later corrections 25.3% (*SD* = 17.8). This suggests that participants' were more likely to exhibit deterministic fixation patters during first corrections but that their total gaze pattern was most dominated by these fixation patterns during later corrections.

We next regressed the proportion of deterministic fixations on trial type using a zero-inflated beta model to test this formally. Here we report the most relevant contrasts pertaining to the descriptive results presented. For the zero-inflation parameter, we found lower likelihood of zero-inflation for first corrected trials compared to control trials (b = -0.73, CrI = [-1.18, -0.28], BF_{10} = 64.8) and later corrected trials (b = -0.88, CrI = [-1.35, -0.37], BF_{10} = 157.6), but not compared to accepted trials (b = -0.35, CrI = [-0.85, 0.16], BF_{10} = 1.55). For the mean parameter of the conditional beta distribution, we found higher average in later corrected trials compared to control trials (b = 0.36, CrI = [0.15, 0.52], BF_{10} = 59.9) and to accepted trials (b = 0.41, CrI = [0.18, 0.63], BF_{10} = 78.0), but not reliably to first corrected trials (b = 0.27, CrI = [-0.01, 0.55], BF_{10} = 1.55). The full model is reported in Supplementary Tables 5-7. Participants were more likely during corrected trials to display repetitions of fixation sequences.

Laminarity (LAM)

Laminarity (LAM) captures contiguous repetitions of fixations to the same point. The pattern of results for laminarity was similar to that for determinism and we report the descriptives the same way. Overall, participants exhibited the least proportion laminarity during control trials 5.6% (*SD* = 10.1), followed by accepted trials 6.1% (*SD* = 8.9) and by later corrected trials 6.6% (*SD* = 12.1), with the highest proportion shown in first corrected trials 9.4% (*SD* = 11.7). Conditional on a laminar sequence being present, for control trials proportion recurrent fixations forming laminar patterns was 13.1% (*SD* = 11.1), for accepted trials 11.8% (*SD* = 9.0), for first corrections 13.1% (*SD* = 11.6), and for later corrections 17.0% (*SD* = 10.8).

We regressed the proportion of laminar fixations on trial type using a zero-inflated beta regression model, reporting the same contrasts as above for determinism. We found lower likelihood of zero-inflation for first corrected trials

Table 1

Contrasts for each time terms and trial types from growth curve analysis of the first 3s of pupil dilation to the feedback screen. Acc = Accepted. Ctrl = Control. 1st Corr = First Corrected. Late

Time term	Contrast	Estimate	CrI	BF_{10}
Linear	Acc-Ctrl	0.52	[0.12, 0.92]	6.7
	1st Corr-Ctrl	1.87	[1.37, 2.34]	$> 10^4$
	Late Corr-Ctrl	1.13	[0.62, 1.64]	514
	1st Corr-Acc	1.34	[0.77, 1.90]	$> 10^4$
	Late Corr-Acc	0.60	[0.034, 1.20]	2.89
	1st Corr-Late Corr	0.74	[0.074, 1.40]	4.96
Quadratic	Acc-Ctrl	-0.14	[-0.44, 0.16]	3.37
	1st Corr-Ctrl	-0.94	[-1.26, -0.62]	$> 10^4$
	Late Corr-Ctrl	-0.31	[-0.62, 0.010]	1.43
	1st Corr-Acc	-0.80	[-1.21, -0.38]	232
	Late Corr-Acc	-0.17	[-0.58, 0.25]	0.41
	1st Corr-Late Corr	-0.63	[-1.07, -0.19]	16.1
Cubic	Acc-Ctrl	0.099	[-0.090, 0.29]	0.23
	1st Corr-Ctrl	-0.15	[-0.39, 0.098]	0.38
	Late Corr-Ctrl	0.28	[0.058, 0.51]	3.08
	1st Corr-Acc	-0.25	[-0.55, 0.051]	0.80
	Late Corr-Acc	0.19	[-0.10, 0.47]	0.46
	1st Corr-Late Corr	-0.43	[-0.76, -0.11]	6.3

compared to control trials (b = -0.90, CrI = [-1.33, -0.45], BF_{10} = 2082.8), later corrected trials (b = -0.94, CrI = [-1.42, -0.46], BF_{10} = 674.3), and to accepted trials (b = -0.50, CrI = [-1.00, 0.00], BF_{10} = 4.10). For the mean parameter of the conditional beta distribution, we found higher average in later corrected trials compared to control trials (b = 0.30, CrI = [0.14, 0.45], BF_{10} = 75.5), to accepted trials (b = 0.44, CrI = [0.22, 0.65], BF_{10} = 157.6), and to first corrected trials (b = 0.33, CrI = [0.05, 0.59], BF_{10} = 4.0). The full model is reported in Supplementary Tables 8-10. Again these results suggest, just as for determinism, that participants were more likely during corrected trials to display repetitions of fixations to the same point on the screen.

Analyses of gaze direction

Face

When viewing the feedback screen, participants gazed at the face 63.0% (SD = 20) of the time during control trials. During accepted trials this proportion was similar (M = 65.1%, SD = 17), but was lower for both first corrected trials (M = 50.1%, SD = 24) and later corrected trials (M = 55.2%, SD = 24).

We regressed the proportion of recorded fixations towards the face AOI on trial type using a zero-one inflated beta model. There were no differences in the inflation parameters hence we focus solely on the the mean parameter of the beta distribution computing contrasts between conditions. We found a tendency, with the Bayes Factor indicating only inconclusive evidence, for a greater proportion of gaze being directed towards the face in accepted trials compared to control trials (b = 0.17, CrI = [0.031, 0.312], BF_{10} = 2.10). However, we found strong evidence for a lower proportion of gaze being directed towards the face during first corrected trials compared to control trials (b = -0.49, CrI = [-0.68, -0.32], $BF_{10} > 10^4$) and to accepted trials (b = -0.67, CrI = [-0.89, -0.44], $BF_{10} > 10^4$), as well as, weak evidence for lower proportion compared to later corrected trials (b = -0.25, CrI = [-0.45, -0.039], BF_{10} = 3.57). During later corrected trials proportion gaze was lower compared to both control trials (b = -0.24, CrI = [-0.40, -0.086], BF_{10} = 10.9) and accepted trials (b = -0.41, CrI = [-0.64, -0.21], $BF_{10} > 115$). The full model is reported in Supplementary Tables 11-14.

We next examined the time course of gaze direction towards the face in the first 3s of each feedback screen viewing using growth curve analysis with cubic orthogonal time terms. First corrected trials differed in the linear component of the trajectories compared to both control trials (b = -0.47, CrI = [-0.71, -0.23], BF_{10} = 203) and to accepted trials (b = -0.49, CrI = [-0.77, -0.21], BF_{10} = 46). Likewise, corrected trials also differed in the linear component of the trajectories compared to both control trials (b = -0.32, CrI = [-0.53, -0.12], BF_{10} = 15.5) and to accepted trials (b = -0.34, CrI = [-0.58, -0.091], BF_{10} = 6.3). All other contrasts indicated evidence for the null of no difference (all $BFs_{10} < 0.34$, see Supplementary Table 15).

Plotting predictions from the model (see Figure 3A) re-

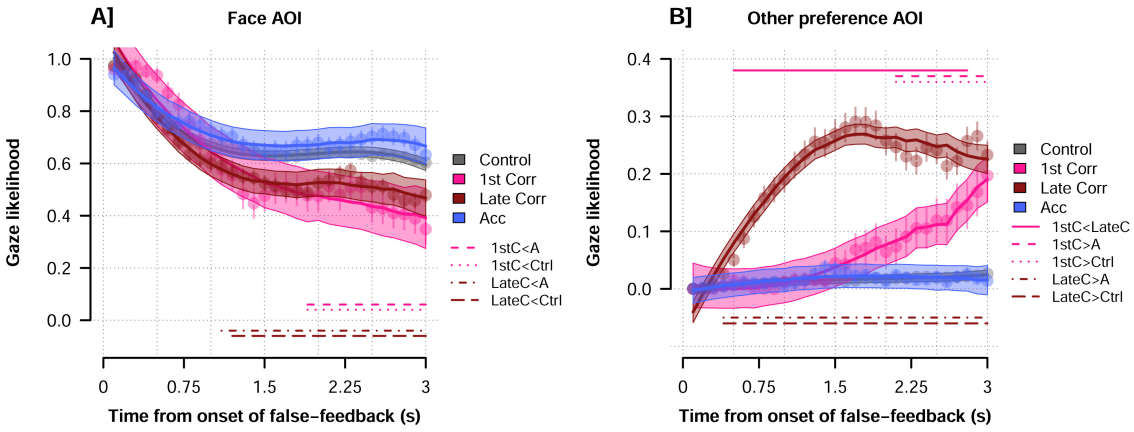

Figure 3

(A] Time course of gaze towards Face AOI. *Average time course of participants gaze towards the Face AOI during the first 3s of viewing the feedback screen. Dots represent observed data and error bars their standard error. Lines are posterior predictions from Bayesian growth curve model and the shaded region represents the 95% credible interval.* ***B] Time course of gaze towards Other preference AOI.*** *Average time course of participants gaze towards the Other preference AOI during the first 3s of viewing the feedback screen.*

vealed differences in the likelihood of gaze being directed towards the face emerge between first corrected trials and accepted and control trials after around 1.9s and being sustained throughout the period of analysis. Differences between later corrected trials and accepted and control trials emerged earlier after around 1s.

Feature buttons

Participants directed their gaze towards the feature buttons 26.3% (*SD* = 17) of the time during control trials. This proportion declined to 22.5% (*SD* = 16) during accepted trials and to 21.7% (*SD* = 16) during first corrected trials. Participants gaze towards feature buttons during later corrected trials only 12.2% (*SD* = 16) of time.

Gaze towards the feature buttons was regressed on trial type using a zero inflated beta regression. Contrasting the mean parameter, we found that participants gazed significantly less at the feature buttons during later corrected trials compared to first corrected trials (b = -0.76, *CrI* = [-1.0, -0.52], $BF_{10} > 10^4$), accepted trials (b = -0.83, *CrI* = [-1.06, -0.60], $BF_{10} > 10^4$) and control trials (b = -1.03, *CrI* = [-1.20, -0.85], $BF_{10} > 10^4$), indicating a clear disinterest in the feature buttons during later corrected trials. This difference did not emerge during first corrected trials against accepted trials (b = -0.06, *CrI* = [-0.32, 0.19], BF_{10} = 0.25), but was just detectable contrasting against control trials (b = -0.06, *CrI* = [-0.32, 0.19], BF_{10} = 0.25), suggesting that participants learn to ignore feature buttons following their first correction. We also found weak evidence for a difference between accepted and control trials, such that features were inspected less on average during accepted trials (b = -0.20, *CrI* = [-0.35, -0.048], BF_{10} = 4.5). Remaining model parameters are reported in the Supplementary Results, as are the results from analysis of the time course of gaze direction toward feature buttons (Supplementary Tables 17-21).

Other preference button

The other preference button functioned to signal correction of the manipulation in our experiment. Unsurprisingly, participants did not direct their gaze towards this button frequently during control trials (*M* = 2.0%, *SD* = 6.4). Interestingly, participants did not appear to gaze much towards it during accepted trials (*M* = 3.7%, *SD* = 7.7), but were considerably more likely to do so during first corrected trials (*M* = 18.2%, *SD* = 13) and later corrected trials (*M* = 22%, *SD* = 20).

Gaze towards the other preference button was regressed on trial type using a zero-inflated beta regression. We found corresponding patterns of results for both the zero-inflation parameter and the mean parameter of the beta distribution. Here we report the mean parameter and report the full model in Supplementary Tables 22-24. We found evidence for the null of no difference when comparing accepted and control trials (b = 0.045, *CrI* = [-0.29, 0.37], BF_{10} = 0.31) and similarly when comparing first and later corrected trials (b = 0.045, *CrI* = [-0.29, 0.37], BF_{10} = 0.31). In line with the descriptive statistics presented above we found strong evidence for more average fixation proportions comparing first corrected trials to both control trials (b = 1.39, *CrI* = [1.25, 1.63], $BF_{10} > 10^4$) and to accepted trials (b = 1.34, *CrI* = [0.97, 1.70], $BF_{10} > 10^4$), and correspondingly when comparing later corrected trials to both control trials (b = 1.55,

CrI = [1.30, 1.78], $BF_{10} > 10^4$) and to accepted trials (b = 1.50, CrI = [1.14, 1.88], $BF_{10} > 10^4$).

Analyzing the time course of gaze direction gave results analogous to those involve gaze towards the face. First corrected trials differed in the linear component of their trajectories compared to both control trials (b = 0.25, CrI = [0.12, 0.38], BF_{10} = 105) and compared to accepted trials (b = 0.26, CrI = [0.13, 0.39], BF_{10} = 92), and corresponding results were also found when contrasting later corrected trials with control trials (b = 0.43, CrI = [0.25, 0.62], $BF_{10} > 10^4$) and accepted trials (b = 0.44, CrI = [0.25, 0.63], $BF_{10} > 10^4$). Additionally, we found strong evidence for the null of no difference in time course when contrasting control and accepted trials for all three time terms (all $BFs_{10} < 0.05$, see Supplementary Table 26). Plotting predictions from the model (see Figure 3B) revealed differences in the likelihood of gaze being directed towards the other preferences emerge between later corrected trials and the other two trials after around 0.5s and being sustained throughout the period of analysis while for first corrected trials differences emerged reliably later - after around 2s.

Card

Lastly we analyzed gaze towards the card that wasn't turned up, and hence should contain the image of the face originally not-chosen. Participants were unlikely to look towards the card at all, with only 0.2% (SD = 3.2) of gaze samples being directed there in control trials. For accepted trials this number was 0.4% (SD = 1.6), for first corrected trials 0.5% (SD = 2.0 and for later corrected trials 0.6% (SD = 4.0).

Gaze towards the card was regressed on trial type using a zero-inflated beta regression. For the mean parameter of the beta distribution we found that later corrected trials differed from control trials (b = 1.05, CrI = [0.62, 1.50], $BF_{10} > 10^4$) and from accepted trials (b = 0.85, CrI = [0.35, 1.35], BF_{10} = 9.9), such that more average fixations were directed towards the card AOI during later corrected trials. Later corrected and first corrected trials did not differ reliably (b = 0.51, CrI = [-0.015, 1.05], BF_{10} = 2.78). First corrected trials did differ from control trials (b = 0.54, CrI = [0.033, 1.06], BF_{10} = 3.78) but not from accepted trials (b = 0.33, CrI = [-0.23, 0.87], BF_{10} = 1.02). Finally, we found no reliable difference between accepted and control trials (b = 0.20, CrI = [-0.25, 0.68], BF_{10} = 0.62; see also Supplementary Tables 27-29). Together this mixed pattern of evidence suggests that while participants are generally unlikely to look towards the card AOI, during trials where they make corrections in later stages of the experiment, they are more likely to spend time looking at the card.

Since overall gaze likelihood was low, we did not conduct an analysis of the time course of gaze direction for this AOI.

Discussion

In this paper we reported results from a process-tracing experiment using pupil dilation, gaze patterns and response times to compare participants' reactions to a choice blindness task. When the participants received false feedback about their choice and subsequently corrected that manipulation we found differences in response times, pupil dilation and gaze patterns compared to both accepted and control trials. Accepted trials differed from control trials by being slower and exhibiting larger pupil dilation, but were similar in their gaze patterns. We first discuss each set of findings separately and then integrate their implications for research on choice blindness as well as the challenge choice blindness poses for relations between intentions and outcomes in choice generally.

When participants corrected the false feedback they exhibited marked differences on a range of measures compared to when they accepted it and to control trial. Additionally, we found substantial differences between first and later corrections, clearly differentiating these trial types from each other. Participants' first corrections were characterized by the longest response times, likely reflecting participants' adjustment to realizing that the choice feedback is false and formulating a response to it. During first corrections participants also exhibited strong and sustained pupillary responses from the onset of the false feedback and onward (see Fig. 2). This increased pupillary response likely reflects initial surprise about the image presented as chosen and the additional processing this requires, suggesting an early recognition that "something is wrong" followed by a protracted search for what the appropriate response to this recognition is. Participants' gaze patterns also differed during first corrections. The results from the recurrence quantification analysis showed that participants exhibited both higher degree of determinism and laminarity in their fixation sequences, driven primarily by lower zero-inflation meaning greater tendency to engage in patterns of repeat fixations during these trials. If first corrections are slow responses triggered by an early recognition that something is wrong with the feedback, there may be less tendency to explore the screen and instead participants engage in simpler and more repetitive gaze patterns to verify this fact. Later corrections, in contrast, were the fastest trial type with the shortest response time. Again participants' pupillary response was heightened from the onset of false feedback and sustained. Participants tended to look first to the face, but disengaged from looking at the presented face faster than for other trial types and instead oriented towards the 'other preference' button which was used to indicate correction of the manipulation. Strikingly, participants also look more towards the card not turned up during later corrected trials. This last detail is important since it might be indicative of behavior similar to as what is found in *looking at nothing* experiments (R. Johansson & Johansson,

2014; Richardson et al., 2009). In this case participants direct their gaze to where task-relevant information could have been present possibly to aid their recall of decision relevant information (R. Johansson & Johansson, 2014; Pärnamets et al., 2016). Therefore, in our view, the pattern of results point towards corrections of the manipulation being clearly a salient and differentiable cognitive event to our participants. Not only did they indicate by overt response that they actually preferred the other face, this response is also accompanied by a very different set of processing measures.

Since accepted trials differed from corrected trials on virtually all relevant measures, the focal comparison for understanding accepted trials is to control trials. Here, the resulting picture is a bit more complicated. Compared to control trials, we see an increase in pupil dilation in accepted trials during deliberation. The increase is of a smaller magnitude than that of the accepted trials, but robustly so (see Fig 2). We also find a difference in reaction time, such that the participants take longer time to reach a decision in accepted trials compared to control trials. However, when analyzing the gaze-patterns of the deliberation process, we find that accepted trials were highly similar to control trials, both in the observed fixation dynamics captured in the recurrence quantification analysis and in the gaze-likelihood analyses. For example, participants show the same tendencies to look at the face and the feature buttons and to not look at the other preference button both when accepting the false feedback and during control trials. The participants are largely doing the same thing in both types of trials - looking at their (believed to be) chosen face and deciding which feature determined their original choice. On balance, we therefore argue that the overall pattern of results indicates that in accepted trials, the participants are in fact unaware of having received the opposite of their choice. This interpretation is further reinforced when combined with the clear processing differences between accepted and rejected trials, and of course the fact that the participants themselves did not reject the outcome received. But if the increase in pupil dilation and response time in accepted trials compared to control trials does not represent conscious awareness of the manipulation, how should it best be understood? One possibility is that in these trials, pupil dilation stems not from expectancy violation, but rather from increased cognitive load or effort stemming from the rationalization process. The longer response times in these trials could also be interpreted this way, indicating an increase in cognitive effort when constructing an answer to why a previously rejected option was the one actually preferred. This interpretation could be further explored measuring electrical brain activity, in particular in relation to error related negativity, while participants are given false feedback on their choices (Falkenstein et al., 1991; Yeung et al., 2004). Following up on this possibility presents a new avenue for research on confabulatory processes, opening a window into how rationalization may differ from veridical self-report.

Can the present study shed further light on choice blindness as such, i.e. why the participants fail to detect the mismatch between what they want and what they get, and why they generate explanations for a choice they only believed they made? First of all, the analysis makes clear that there are genuine processing differences between accepted and corrected manipulated trials. This reinforces the assumption that the act of accepting or correcting the altered outcome also represents two different psychological states in the participants; one in which they are aware of the manipulation, and one in which they are not. Thus, we hope that the current study will put to rest any lingering doubts that the phenomenon of choice blindness may be due to some sort of elaborate experimental demand effect, or the like Jack, 2013; J. Moore and Haggard, 2006. Similarly, lack of attention to the received option can not be an explanation for choice blindness, given the broad similarities in gaze patterns between accepted and control trials. It is clear that in accepted trials, the participants look at the manipulated face after presentation. Therefore, participants' report of correction is a reliable measure of whether they have been aware of the manipulation or not.

If we return to the folk-psychological intuition outlined in the introduction, choice blindness is noteworthy as it challenges our commonsense assumption of a tight link between our intentions and the outcome of our actions (P. Johansson et al., 2005; J. W. Moore et al., 2009). In error monitoring models, the fundamental assumption is that the brain implements continuous performance monitoring in relation to predefined goal states or intentions (Ridderinkhof et al., 2004; Ullsperger & von Cramon, 2004). Among many things, comparing the outcome of our choices with prior intentions is thought to enable error correction by separating deliberate from accidental outcomes, and what we have done from what we plan to do (Sugimori et al., 2013). Nevertheless, choice blindness does not show that people are *unable* to access or process cognitions they had while deliberating their decision. Instead, the phenomenon implies that one's attitude to the option presented post-choice does not necessarily follow from those prior cognitions. Indeed, past work has shown that memory failures cannot account for the occurrence of choice blindness (Sagana et al., 2014b). As we see it, the mistake to make is to assume that the intentions involved in preferential choice have the same kind of specificity as for simple motor commands, from which error monitoring models often originates (c.f. Wolpert et al., 2013). This issue has been extensively explored in the domain of manual actions, where a contrast has been made between comparator and inferential models of sense of agency (Kühn et al., 2013; Synofzik et al., 2008). Inferential models see attribution of agency as a contextual, evidence based process that can often be confused under both natural and experimental conditions (Lind et al.,

2014a; J. W. Moore et al., 2009; Wegner & Wheatley, 1999). Inferential models do not deny that people sometimes might formulate very clear and detailed accounts of what they prefer. Similarly, they do not deny that error correction exists. What is denied is only that the sense of agency of one's actions is produced by a dedicated mechanism monitoring mismatches between intentions and outcomes.

The operation of such an inferential process is supported by the pattern of results in this study, particularly for accepted manipulated trials. Beyond the present study, there is considerable evidence both from choice blindness and elsewhere that preferences are constructed during choice and reconstructed from memory after choice (P. Johansson et al., 2014; Slovic, 1995; Strandberg et al., 2018; Warren et al., 2011). Hence, when facing false feedback, it is likely participants try to remember features of their previously chosen option and attempt to compare this with the presented outcome. Memory for features of choices is incomplete and prone to biases (Mather et al., 2000), and participants must integrate this noisy evidence with the (false) information presented to them in the task environment. Along these lines, previous work has shown that more similar choice sets lead to fewer corrections (P. Johansson et al., 2005) and participants who are more careful reasoners make more corrections (Strandberg et al., 2018).

Choice blindness shows how powerful an influence the environment can be for our self-representation, and how heavily we rely on the world as a model for itself (Brooks, 1991; Pärnamets, Johansson, et al., 2020). By studying the dynamics of false feedback and correction in the choice blindness paradigm we can hope to attain a more fine-grained model of how the task environment interacts with cognitive systems during choice. Furthermore, given the possibilities of using choice blindness not only to study our reactions to feedback in the environment, but how beliefs in our choice build our future preferences (P. Johansson et al., 2014; Pärnamets, von Zimmermann, et al., 2020) and ideological leanings (Strandberg et al., 2020; Strandberg et al., 2018), understanding these processes is of continued importance to our understanding of ourselves as imperfect cognitive agents.

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