Visual awareness judgments are sensitive to the outcome of performance monitoring.

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Abstract

Can previous mistakes influence our visual awareness? In this study we tested the hypothesis that perceptual awareness judgments are sensitive to the results of performance monitoring, and specifically to internal or external accuracy feedback about previous behaviour. We used perceptual discrimination task in which participants reported their stimulus awareness. We created two conditions: No-feedback and Feedback (discrimination accuracy feedback at the end of each trial). The results showed that visual awareness judgments are related to the accuracy of current and previous response. Participants reported lower stimulus awareness for incorrectly versus correctly discriminated stimuli in both conditions, but also lower awareness level in correct trials preceded by trials in which discrimination was incorrect, compared to trials preceded by correct discrimination. This difference was significantly stronger in Feedback condition. Moreover, in Feedback condition we observed "post-error slowing" for both discrimination response and PAS rating. We discuss the relation between the effects of performance monitoring and visual awareness and interpret the results in the context of current theories of consciousness.

Keywords: visual awareness, PAS, performance monitoring, error detection, feedback

Introduction

Can previous mistakes influence our visual awareness? Do we learn to see things more clearly? Although factors modulating visual perception have been extensively studied, less is known about how visual experience is formed. Studies that investigated subjective aspects of vision have shown that visual awareness of a given stimulus depends not only on the sensory data, but also on perceiver's attention (e.g. Koivisto & Silvanto, 2011; Koivisto & Silvanto, 2012), expectations (Melloni, Schwiedrzik, Muller, Rodriguez & Singer, 2011; Pinto, van Gaal, de Lange, Lamme, & Seth, 2015) and even stimulus-related actions (Siedlecka, Hobot, Skóra, Paulewicz, Timmermans, & Wierzchoń, 2018). Following recent findings on the relation between motor activity and subjective aspects of perception (Fleming, Maniscalco, Ko, Amendi, Ro, & Lau, 2015; Gajdos, Fleming, Saez Garcia, Weindel, & Davranche, 2018; Siedlecka et al., 2018) we attempted to investigate whether judgments of visual experience are sensitive to internal and external evaluation of one's performance in perceptual task.

Perception processing can be assessed by objective measures, such as forced-choice discrimination or signal detection. Perceptual awareness, however, is accessed through first-person reports given by the perceivers. For example, during a perceptual decision task a person might be asked to rate clarity of her visual experience using Perceptual Awareness Scale (PAS, Ramsøy & Overgaard, 2004) or simply report stimulus visibility (Sergent & Dehaene, 2004). Indirect measures, such as confidence in stimulus-related choices are also used (Cheesman & Merikle, 1986). In recent years it has been shown that perceptual confidence correlates with some characteristics of the stimuli-related response, such as response time in discrimination task (Fleming, Massoni, Gajdos, & Vergnaud, 2016; Kiani, Corthell, & Shadlen, 2014) or presence of muscle preparatory activity (Gajdos et al., 2018), and it is also affected by changes in cortical motor representations (Fleming et al., 2015). Action has also been observed to influence visual awareness ratings (Siedlecka et al., 2018). In this study participants rated their perceptual awareness of near-threshold stimuli after carrying out a cued response that was either congruent, incongruent or neutral in respect to the correct stimulus-related response. Lower PAS ratings were observed in neutral condition suggesting that stimulus-related motor response elevates visual awareness of this stimulus. These findings reveal that action-related information, such as response time, fluency or internal accuracy feedback can inform perceptual judgements.

If visual awareness of stimulus can be affected by stimulus-related response, does it also depend on evaluation of the previous action? Theories that describe visual consciousness in terms of metarepresentations of the first-order perceptual states suggest that visual experience results from learning. For example, the higher-order Bayesian decision theory of consciousness (Lau, 2008) assumes that brain learns to distinguish which of its own internal states represent the external stimuli. As a result of this learning process criterion for which state becomes represented consciously changes (e.g. becomes more conservative). Cleeremans and colleagues (Cleeremans, 2011; Timmermans, Schilbach, Pasquali & Cleeremans, 2012) describe consciousness as a result of brain learning the neural consequences of its own activity and actions, increasing the precision of its representations (whether it sees or does not see something). Learning can therefore improve the ability to access perceptual information which was shown by the a metacontrast masking study in which extensive training in discrimination task with accuracy feedback increased perceptual awareness for correctly discriminated stimuli (Schwiedrzik, Singer, & Melloni, 2009).

The question asked in this paper is whether perceptual awareness can be influenced by the current changes in perceptual performance level, that is whether it is sensitive to the outcome of on-line performance monitoring. Research on motor control suggests that there are systems specialised in monitoring and regulating task-related behaviour that detect difficulties and errors in order to adjust the level of top-down control (Botvinick, Cohen, & Carter, 2004; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). This monitoring does not have be done intentionally and its results are not necessarily consciously perceived (Endrass, Reuter, & Kathmann, 2007; Nieuwenhuis, Schweizer, Mars, Botvinick, & Hajcak, 2007; Wessel, Danielmeier, & Ullsperger, 2011) but they do affect subsequent behaviour. For example, in speed-response tasks, after an error was committed participants respond slower (co-called post-error slowing, Dutilh, Vandekerckhove, Forstmann, Keuleers, Brysbaert, & Wagenmakers, 2012; Notebaert, Houtman, Van Opstal, Gevers, Fias, & Verguts, 2009; Rabbitt, 1966) and make less mistakes, therefore adapt their performance speed in order to achieve a certain level of accuracy (Veen & Carter, 2006). There are several theories explaining how error can be detected, but the most popular ones state that it stems from comparison between required and launched response (Coles, Scheffers, & Holroyd, 2001; Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Gehring, Gross, Coles, Meyer, & Donchin, 1993) or from conflict between simultaneously evolving response tendencies (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, et al., 2004). The erroneous responses are accompanied by electrophysiological changes in brain activity, such as so-called error-related negativity (ERN, Gehring et al., 1993) followed by a positive component, Pe (see e.g. Boldt & Yeung, 2015; Wessel, 2012). Similarly, explicit information about an error is accompanied by a feedback-related negativity (FRN, e.g. Luu, Tucker, Derryberry, Reed, & Poulsen, 2003), and has also been shown to influence subsequent behaviour (Derryberry, 1991; Luu et al., 2003).

It is not clear what is the relation between the results of performance monitoring and awareness. The level of perceptual confidence is usually lower when person responds incorrectly in decisional task (Kiani et al., 2014; Petrusic & Baranski, 2003), but this relation could simply reflect the influence of sensory data quality on both, objective and subjective aspects of perception (the less perceptual evidence to higher probability of making mistake and lower level of stimulus awareness). Also, studies on error-detection are not consistent when it comes to the relation between error-related neural activity and error awareness, however the amplitude of ERN and Pe has been shown to correlate with choice confidence (Bold & Yeung, 2015; Charles, Van Opstal, Marti, & Dehaene, 2013; Scheffers & Coles, 2000; Steinhauser & Yeung, 2012).

In this study we tested the hypothesis that visual awareness judgments are sensitive to the results of performance monitoring, and specifically to internal or external accuracy feedback about previous behaviour. We used perceptual discrimination task in which participants also reported their stimulus awareness. Half of the trials were followed by explicit feedback about discrimination accuracy. We expected that reported awareness level would be affected by the accuracy of the previous trials, especially in blocks with feedback information. Specifically, we hypothesised that awareness ratings would decrease after erroneous trials, due to threshold adjustment. However, it is also plausible, that information about error would raise reported awareness level, by increasing top-down attention and amplifying related sensory signal (Fazekas & Overgaard, 2018).

Methods

Participants

Thirty four healthy volunteers (7 males), aged 22 (SD = 2.88) took part in experiment in return for a small payment. All participants had normal or corrected to normal vision and gave written consent to participation in the study. The ethical committee of the Institute of Psychology, Jagiellonian University approved the experimental protocol.

Materials

The experiment was run on PC computers using PsychoPy software (Peirce, 2007). We used LCD monitors (1280 x 800 pixels resolution, 60-Hz refresh rate). The keyboard buttons were labelled both for orientation responses ("L" and "R" on the left side of the keyboard) and PAS scale responses ("1"-"4" numbers on the right side of the keyboard). The stimuli were Gabor gratings oriented towards left (-45 degrees) or right (45 degrees), embodied in a visual noise, presented in the centre of the screen against a grey background. The visual angle of the stimuli was around 3°. The contrast of the stimuli was determined for each participant during a calibration session.

The PAS was presented with the question: 'How clear your experience of stimulus was?' and the options were: 'no experience', 'a brief glimpse', 'an almost clear experience', and 'a clear experience'. The meaning of the individual scale points was explained in the instruction. The description of each point was based on a guide by Sandberg & Overgaard (2015) with some modifications related to the characteristics of stimuli that were relevant in this experiment (i.e. "no experience" was associated with no experience of the Gabor stripes, but "a brief glimpse" with an experience of "something being there" but without the ability to decide the orientation of the stripes).

Procedure

The experiment was run in a computer laboratory. Two within-subject conditions were introduced: with and without accuracy feedback. All trials began with a blank presentation (500 ms), followed by a fixation cross (500 ms). The grating embedded in white noise was presented for 33 ms. Participants were asked to respond whether the grating was oriented towards the left or the right side. The first part started with 15 training trials, in which stimuli was clearly visible (presented at colour in rgb space = [0.3,0.3,0.3] and opacity = 1). Participants were asked to discriminate gabor orientation and they received accuracy feedback. Then, the calibration procedure was used to estimate the stimulus contrast resulting in about 70% of correct discrimination response. There were 150 trials with 1 up, 2 down staircase (stair-size 0.005, limit for 0.02 and 0.08) and the contrast was established based on the last 100 trials. The calibration procedure was followed by a break. Afterwards, the second session started with 15 training trials in which PAS scale was presented after discrimination response.

After the second training session two experimental blocks followed; with feedback and without feedback (the order was counterbalanced between participants). Each experimental block consisted of 200 trials. Then participants were asked to respond to the discrimination task and PAS. In feedback condition the responses were followed by information about discrimination accuracy. The time limit for all responses was 3 seconds. Participants were asked to respond as quickly and as accurately as possible. The time of feedback presentation was half a second. The outline of the procedure is presented on the Figure 1.

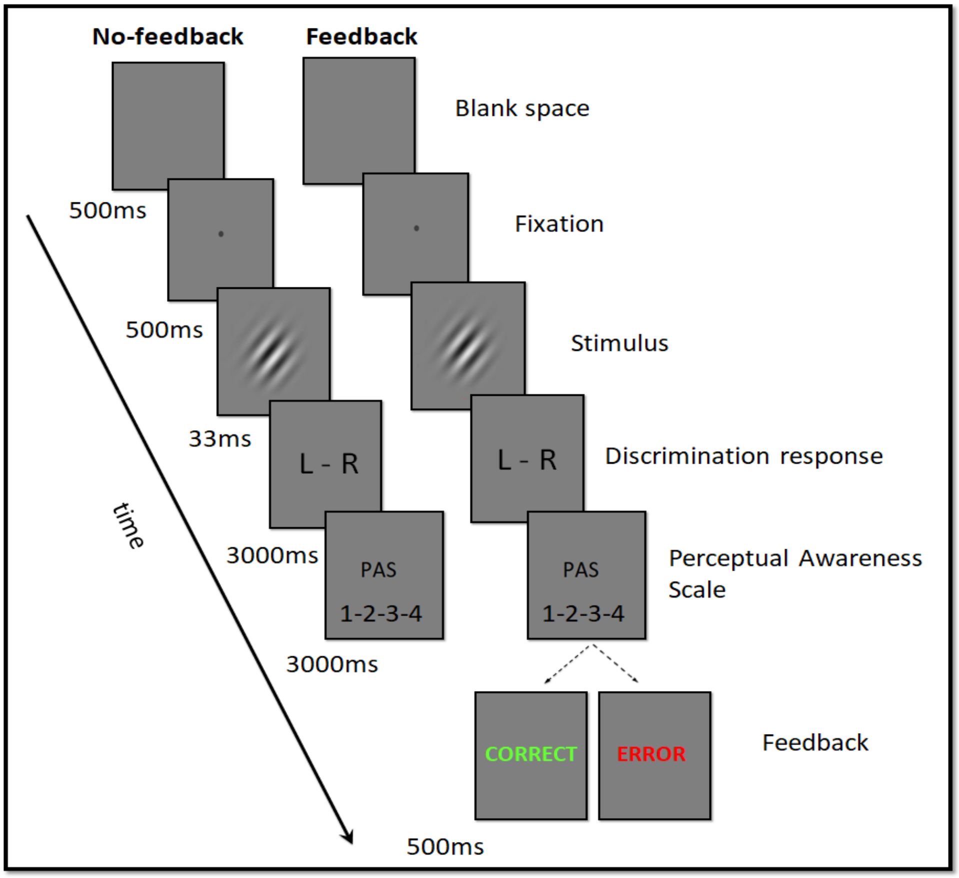

Figure 1. The outline of the procedure. Participants started either with Feedback or No-feedback block.

Results

We excluded 1 participants' data from analysis due to poor performance (49% accuracy). Next, we removed omitted trials (discrimination and scale rating) and discrimination response times slower than 100 ms. We did not detect significant differences between conditions in accuracy (Feedback: 78%, No-feedback: 75%; z = -1.62, p = .11). Signal-detection analyses conducted on discrimination task did not reveal statistically significant differences between conditions neither in d' (z = -1.31, p = .19), nor in response bias (z = 1.48, p = .14). The general descriptive statistics are presented in Table 1.

Table 1. Average response time and PAS ratings for different types of discrimination responses: erroneous, correct, correct followed by correct (CC) and correct followed by errors (EC)

Condition	Type of response	Mean RT (ms) (SD)	Mean PAS (SD)	Frequency
Feedback	error	879 (376)	1.95 (0.82)	12%
	correct	799 (321)	2.47 (0.92)	38%
	correct after correct (CC)	775 (288)	2.55 (0.90)	29%
	correct after error (EC)	825 (349)	2.13 (0.89)	13%
No feedback	error	824 (412)	1.95 (0.78)	14%
	correct	773(313)	2.34 (0.85)	36%
	correct after correct (CC)	780 (302)	2.35 (0.83)	25%
	correct after error (EC)	761 (339)	2.18 (0.80)	20%

The relation between current trial accuracy and PAS ratings

To test the relationship between the accuracy of a given trial and PAS ratings we fitted mixed logistic regression model using lme4 package in the R Statistical Environment (Bates, Maechler, Bolker, & Walker, 2015; R Core Team, 2015). Statistical significance was assessed with the Wald test. The model included following fixed effects: PAS rating, condition and their interactions as well as the random effects of participant-specific intercept and slope. The intercept informs about performance level when participants report having no experience of the stimulus (criterion), while regression slope reflects the relation between PAS rating and discrimination accuracy. Relationship between accuracy and PAS ratings was statistically significant, meaning that correct responses were followed by higher PAS ratings ($z = 5.65$, $p < .001$), and we did not detect significant differences between the conditions in the strength of this relation ($z = 3.31$,$p = .76$). Additionally, we observed that participants' performance level was significantly higher than chance level when participants reported having no experience of stimulus ($z= 3.36$, $p< .001$) and we found no significant differences in this respect between conditions ($z= 0.14$, $p = .89$). We also performed another analysis including only the first blocks in each condition, because when Feedback block was run first participants had been given a chance to improve their metacognitive awareness before getting to the No-feedback block. However, this analysis revealed the same pattern of results.

The relation between previous trial accuracy and PAS ratings

This analysis was carried out to find out whether feedback modulates stimulus awareness ratings. We compared PAS ratings between correct trials preceded by correct trials and correct trials preceded by errors. Linear mixed model with random effect of previous accuracy, condition and their interaction revealed that in both conditions participants reported lower stimulus awareness in trials preceded by erroneous trials compared to trial preceded but correct ones (Feedback: $t = 7.76$, $p < .001$; No-Feedback: $t = 3.89$, $p < .001$). However, this difference was bigger in the Feedback condition ($t = 2.86$, $p < 0.01$). Similarly, response times to PAS rating were given later if the current trial followed an erroneous trial, but only in the Feedback condition ($t = 5.3$, $p < .001$). We did not find significant difference for No-feedback condition ($t = 0.78$,$p < .43$).

To find out whether feedback modulates the way in which accuracy of previous response relates to the response time in a current trial we fitted Linear Logistic Mixed Model with the reaction time as dependent variable. The CC stands for a correct trial preceded by a correct trial and EC stands for a correct trial preceded by an error. We observed post-error slowing, that is significantly longer response times after errors, in Feedback condition ($t= 3.71$, $p < .001$). The difference between the CC and EC trials was significantly bigger in Feedback condition than in No-feedback condition ($t= 2.94$, $p < .01$), where this difference was not statistically significant ($t= -0.26$, $p = .79$).

Discussion

The question of whether the results of performance monitoring could affect perceptual awareness follows naturally the findings revealing links between stimulus-related action and subjective report (Gajdos et al., 2018; Fleming et al., 2015; Kiani et al., 2014; Siedlecka et al., 2018). The results of the presented study shows that visual awareness is related to the accuracy of current and previous response. Participants reported lower stimulus awareness for incorrectly versus correctly discriminated stimuli in both conditions, with and without explicit accuracy feedback. Moreover, participants reported lower stimulus awareness in correct trials preceded by trials in which discrimination was incorrect, compared to trials preceded by correct discrimination. This difference was significantly stronger in the condition with accuracy feedback. Moreover, in Feedback condition we observed "post-error slowing" for both discrimination response and PAS rating: reaction times were longer for correct trials preceded by error compared to the trials preceded by correct responses.

The results suggest that visual awareness judgements are sensitive to the evaluation of one's previous performance, both internal and external. Since perceptual awareness ratings were lower following trials with erroneous response, it seems that neither error itself nor negative feedback increase the level of perceptual awareness by engaging more attentional resources, but rather that performance evaluation results in adjusting subjective criteria for different levels of awareness. This supports the view of the effects of learning on visual consciousness. For example, according to Lau (Lau, 2008) what is consciously perceived depends on the decisional criterion that is set based on learning one's own internal signal. The criterion can be set too high or too low (cases of blindsight and hallucinations, respectively), but it can also change in some conditions resulting in different stimulus awareness level for the same stimulus quality (Lau and Passingham, 2006).

Some theories of consciousness assume that information about error could be integrated into higher-order representation (Cleeremans, 2011; Timmermans et al., 2012), however the exact mechanisms have not been described. Studies on performance monitoring suggest that apart from changes in brain electrical activity (Boldt & Yeung, 2015; Gehring et al., 1993; Wessel, 2012; Wiens et al., 2011) errors also involve response of the autonomic nervous system, such as changes in heart rate (Fiehler, Ullsperger, Grigutsch, & von Cramon, 2004; Hajcak, McDonald, & Simons, 2003; Wiens et al., 2011), skin conductance and pupil diameter (O'Connell, Dockree, Bellgrove, Kelly, Hester, Garavan, Robertson, & Foxe, 2007; Critchley, Tang, Glaser, Butterworth, & Dolan, 2005). Although the are studies and theories explaining how and when people become aware of their errors (e.g. Charles et al., 2013; Wiens et al., 2011) little is known about how carrying out stimulus-related erroneous response affects stimulus awareness. The most plausible explanation is that the results of performance monitoring, gathered from different sources (response conflict, proprioceptive and interoceptive feedback from erroneous action) are integrated into conscious representation of a stimulus. Studies also show that error-related evidence accumulates over time (Ullsperger, Harsay, Wessel, & Ridderinkhof, 2010), therefore it could be reflected not only in the immediate awareness rating but also in a delayed one (in a following trial).

Information about error can be processed outside of awareness but it could also influence perceptual judgments via metacognitive feelings associated with detected processing difficulties or fluency. For example, participants rate incongruent trials in Stroop task as more difficult and report a stronger "urge to err" (Morsella, Gray, Krieger, & Bargh, 2009; Morsella, Wilson, Berger, Honhongva, Gazzaley, & Bargh, 2009). In a study on perceptual discrimination in which targets were primed by either congruent or incongruent primes, trials that were congruent, fast, or required the same response as the previous trial were rated by participants as easy compared to trials that were incongruent, slow, and required a different response (Desender, Van Opstal, & Van den Bussche, 2017). In studies on metamemory, processing fluency (e.g. manipulated by the size of the font in which words to be learned are written, Rhodes & Castel, 2008) has been shown to influence metacognitive judgments.

Although in our study PAS ratings were related to the current and previous trials accuracy independently of external feedback, they were also affected by feedback. Not only it increased the difference between PAS ratings in trials following correct and incorrect trials, it also affected the latency of discrimination response and PAS rating. These results suggest that explicit accuracy information adds to the internally generated effects of performance monitoring and results in adjusting the speed of response (more cautious strategy). Interestingly however we did not find general effect of feedback on subjective criterion level or on the relation between response accuracy and PAS level. More studies are needed to more precisely establish the links between accuracy feedback and awareness judgments. Different types of feedback might differentially affect stimuli awareness. For example, in the only study know to us, in which the effect of feedback on perceptual awareness was tested, participants first undergone extensive perceptual orientation training (five days) with accuracy feedback but without PAS ratings. In the post-training session their perceptual sensitivity and stimulus awareness of correctly discriminated stimuli has been shown to increase (Schwiedrzik et al., 2009). One could assume that since performance feedback has been shown to increase perceptual accuracy (Herzog, &

Fahle, 1997; Seitz, Nanez, Holloway, Tsushima, & Watanabe, 2006; Schwiedrzik et al., 2009) it would also increase awareness. Interestingly, in other studies where perceptual awareness has not been measured, false positive feedback (after the whole block) also improved perceptual discrimination accuracy (Shibata, Yamagishi, Ishii, & Kawato, 2009; Zacharopoulos, Binetti, Walsh, & Kanai, 2014). A promising direction for future studies would be to test the effect of trial by trial false feedback in order to dissociate the effects of real discrimination accuracy and feedback information on stimulus awareness ratings.

One limitation of the current study is that we do not differentiated between two kinds of errors - premature responses, when participants pressed the wrong key by accident, from errors resulting from "data limitation" (Scheffer & Coles, 2000). The first type is perceived as error, whereas the second type results from uncertainty about the stimulus characteristics. We presume that as the time available for responses was quite long (3 s) and stimulus duration was short (33ms) most errors where the second type. However, we can exclude the possibility that perceived and non-perceived errors are differently related to the level of stimulus awareness. At the same time, the feedback condition have provided participants with clear error information despite the type of error.

The results of the present experiment could also be seen as challenging the claim that perceptual awareness ratings refer directly to one's visual experience of a stimulus and are not related to evaluation of one's performance (Sandberg, Timmermans, Overgaard, & Cleeremans, 2010). If we adopt the view that awareness report is just a type of metacognitive judgment, we can interpret the results in the broader context of studies on metacognition. It has been shown that such judgments are informed by different types of information. For example, Fleming's model of self-evaluation judgments assumes, that metacognitive process assess not only the internal evidence for a decision, but also one's performance (e.g. by detecting errors, Fleming & Daw, 2017). Confidence judgments have been shown to correlate with the speed and accuracy of the immediately preceding decision (Fleming et al., 2016; Kiani et al., 2014; Siedlecka, Skóra, Paulewicz, Timmermans, & Wierzchoń, 2018). Interestingly however, although confidence has also been shown to depend on confidence in previous trial ((Fleming et al., 2016; Rahnev, Koizumi, McCurdy, D'Esposito, & Lau, 2015), no such effect has been described for perceptual discrimination accuracy.

Bibliography

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software, 67(1), 1-48.

Boldt, A., & Yeung, N. (2015). Shared neural markers of decision confidence and error detection. Journal of Neuroscience, 35(8), 3478-3484.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. Psychological Review, 108(3), 624-652.

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: an update. Trends in Cognitive Sciences, 8(12), 539-546.

Charles, L., Van Opstal, F., Marti, S., & Dehaene, S. (2013). Distinct brain mechanisms for conscious versus subliminal error detection. NeuroImage, 73, 80–94. https://doi.org/10.1016/j.neuroimage.2013.01.054

Cheesman, J., & Merikle, P. M. (1986). Distinguishing conscious from unconscious perceptual processes. Canadian Journal of Psychology/Revue Canadienne de Psychologie, 40(4), 343-376.

Cleeremans, A. (2011). The radical plasticity thesis: how the brain learns to be conscious. Frontiers in Psychology, 2, 86.

Cleeremans, A., & French, R. (2013). Implicit Learning and Consciousness: An Empirical, Philosophical and Computational Consensus in the Making. Psychology Press.

Coles, M. G. ., Scheffers, M. K., & Holroyd, C. B. (2001). Why is there an ERN/Ne on correct trials? Response representations, stimulus-related components, and the theory of error-processing. Biological Psychology, 56(3), 173-189.

Critchley, H. D., Tang, J., Glaser, D., Butterworth, B., & Dolan, R. J. (2005). Anterior cingulate activity during error and autonomic response. Neuroimage, 27, 885-895.

Derryberry, D. (1991). The immediate effects of positive and negative feedback signals. Journal of Personality and Social Psychology, 61(2), 267-278.

Desender, K., Van Opstal, F., & Van den Bussche, E. (2017). Subjective experience of difficulty depends on multiple cues. Scientific Reports, 7, 44222.

Dutilh, G., Vandekerckhove, J., Forstmann, B. U., Keuleers, E., Brysbaert, M., & Wagenmakers, E. J. (2012). Testing theories of post-error slowing. Attention, Perception, & Psychophysics, 74(2), 454-465.

Endrass, T., Reuter, B., & Kathmann, N. (2007). ERP correlates of conscious error recognition: aware and unaware errors in an antisaccade task. European Journal of Neuroscience, 26(6), 1714-1720.

Falkenstein, M., Hoormann, J., Christ, S., & Hohnsbein, J. (2000). ERP components on reaction errors and their functional significance: a tutorial. Biological psychology, 51(2-3), 87-107.

Fazekas, P., & Overgaard, M. (2018). A Multi□factor account of degrees of awareness. Cognitive Science, 42(6), 1833-1859.

Fiehler, K., Ullsperger, M., Grigutsch, M., & von Cramon, D. (2004). Cardiac responses to error processing and response conflict. In M. Ullsperger & M. Falkenstein (Eds.), Errors, conflicts, and the brain. Current opinions on performance monitoring (pp. 135–140). Leipzig: MPI for Human Cognitive and Brain Sciences.

Fleming, S. M., & Daw, N. D. (2017). Self-evaluation of decision-making: A general Bayesian framework for metacognitive computation. Psychological Review, 124(1), 91–114.

Fleming, S. M., Maniscalco, B., Ko, Y., Amendi, N., Ro, T., & Lau, H. (2015). Action-Specific Disruption of Perceptual Confidence. Psychological Science, 26(1), 89-98.

Fleming, S. M., Massoni, S., Gajdos, T., & Vergnaud, J. C. (2016). Metacognition about the past and future: quantifying common and distinct influences on prospective and retrospective judgments of self-performance. Neuroscience of Consciousness, 2016(1).

Gajdos, T., Fleming, S., Saez Garcia, M., Weindel, G., & Davranche, K. (2018). Revealing subthreshold motor contributions to perceptual confidence. BioRxiv. https://doi.org/10.1101/330605

Gehring, W. J., Goss, B., Coles, M. G., Meyer, D. E., & Donchin, E. (1993). A neural system for error detection and compensation. Psychological science, 4(6), 385-390.

Hajcak, G., McDonald, N., & Simons, R. F. (2003). To err is autonomic: Error-related brain potentials, ANS activity, and post-error compensatory behavior. Psychophysiology, 40, 895-903.

Herzog, M. H., & Fahle, M. (1997). The role of feedback in learning a vernier discrimination task. Vision research, 37(15), 2133-2141.

Kaplan, J. T., & Zaidel, E. (2001). Error monitoring in the hemispheres: the effect of lateralized feedback on lexical decision. Cognition, 82(2), 157-178.

Kiani, R., Corthell, L., & Shadlen, M. N. (2014). Choice Certainty Is Informed by Both Evidence and Decision Time. Neuron, 84(6), 1329-1342.

Koivisto, M., & Silvanto, J. (2011). Relationship between visual binding, reentry and awareness. Consciousness and Cognition, 20(4), 1293-1303.

Koivisto, M., & Silvanto, J. (2012). Visual feature binding: The critical time windows of V1/V2 and parietal activity. NeuroImage, 59(2), 1608-1614.

Lau, H. C. (2007). A higher order Bayesian decision theory of consciousness. In Progress in Brain Research (Vol. 168, pp. 35-48). Elsevier.

Lau, H. C., & Passingham, R. E. (2006). Relative blindsight in normal observers and the neural correlate of visual consciousness. Proceedings of the National Academy of Sciences, 103(49), 18763-18768.

Luu, P., Tucker, D. M., Derryberry, D., Reed, M., & Poulsen, C. (2003). Electrophysiological responses to errors and feedback in the process of action regulation. Psychological Science, 14(1), 47-53.

Melloni, L., Schwiedrzik, C. M., Müller, N., Rodriguez, E., & Singer, W. (2011). Expectations change the signatures and timing of electrophysiological correlates of perceptual awareness. The Journal of Neuroscience: The Official Journal of the Society for Neuroscience, 31(4), 1386-1396.

Morsella, E., Gray, J. R., Krieger, S. C., & Bargh, J. A. (2009). The essence of conscious conflict: subjective effects of sustaining incompatible intentions. Emotion, 9(5), 717-728.

Morsella, E., Wilson, L. E., Berger, C. C., Honhongva, M., Gazzaley, A., & Bargh, J. A. (2009). Subjective aspects of cognitive control at different stages of processing. Attention, Perception, & Psychophysics, 71(8), 1807-1824.

Nieuwenhuis, S., Schweizer, T. S., Mars, R. B., Botvinick, M. M., & Hajcak, G. (2006). Error-likelihood prediction in the medial frontal cortex: a critical evaluation. Cerebral Cortex, 17(7), 1570-1581.

Notebaert, W., Houtman, F., Van Opstal, F., Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: an orienting account. Cognition, 111(2), 275-279.

O'Connell, R. G., Dockree, P. M., Bellgrove, M. A., Kelly, S. P., Hester, R., Garavan, H., Robertson, J., & Foxe, J. (2007). The role of cingulate cortex in the detection of errors with and without awareness: A high-density electrical mapping study. European Journal of Neuroscience, 25, 2571-2579.

Petrusic, W. M., & Baranski, J. V. (2003). Judging confidence influences decision processing in comparative judgments. Psychonomic bulletin & review, 10(1), 177-183.

Pinto, Y., van Gaal, S., de Lange, F. P., Lamme, V. A. F., & Seth, A. K. (2015). Expectations accelerate entry of visual stimuli into awareness. Journal of Vision, 15(8), 13.

R Core Team (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Rabbitt, P. M. (1966). Errors and error correction in choice-response tasks. Journal of experimental psychology, 71(2), 264-272.

Rahnev, D., Koizumi, A., McCurdy, L. Y., D'Esposito, M., & Lau, H. (2015). Confidence leak in perceptual decision making. Psychological Science, 26(11), 1664-1680.

Ramsøy, T. Z., & Overgaard, M. (2004). Introspection and subliminal perception. Phenomenology and the Cognitive Sciences, 3(1), 1-23.

Ridderinkhof, K. R., Ullsperger, M., Crone, E. A., & Nieuwenhuis, S. (2004). The role of the medial frontal cortex in cognitive control. Science, 306(5695), 443-447.

Rhodes, M. G., & Castel, A. D. (2008). Memory predictions are influenced by perceptual information: evidence for metacognitive illusions. Journal of experimental psychology: General, 137(4), 615-625.

Sandberg, K., Timmermans, B., Overgaard, M., & Cleeremans, A. (2010). Measuring consciousness: is one measure better than the other?. Consciousness and cognition, 19(4), 1069-1078.

Scheffers, M. K., & Coles, M. G. (2000). Performance monitoring in a confusing world: error-related brain activity, judgments of response accuracy, and types of errors. Journal of Experimental Psychology: Human Perception and Performance, 26(1), 141-151.

Schwiedrzik, C. M., Singer, W., & Melloni, L. (2009). Sensitivity and perceptual awareness increase with practice in metacontrast masking. Journal of Vision, 9(10), 18-18.

Seitz, A. R., Nanez, J. E., Holloway, S., Tsushima, Y., & Watanabe, T. (2006). Two cases requiring external reinforcement in perceptual learning. Journal of vision, 6(9), 9-9.

Sergent, C., & Dehaene, S. (2004). Is consciousness a gradual phenomenon? Evidence for an all-or-none bifurcation during the attentional blink. Psychological Science, 15(11), 720-728.

Shibata, K., Yamagishi, N., Ishii, S., & Kawato, M. (2009). Boosting perceptual learning by fake feedback. Vision research, 49(21), 2574-2585.

Siedlecka, M., Hobot, J., Skora, Z., Paulewicz, B., Timmermans, B., & Wierzchon, M. (2018). Motor Responses Influence Perceptual Awareness Judgements. bioRxiv, 283762.

Siedlecka, M., Skóra, Z., Paulewicz, B., Fijalkowska, S., Timmermans, B., & Wierzchon, M. (2018). Responses improve the accuracy of confidence judgements in memory tasks. Journal of Experimental Psychology: Learning, Memory and Cognition.

Steinhauser, M., & Yeung, N. (2012). Error awareness as evidence accumulation: effects of speed-accuracy trade-off on error signaling. Frontiers in Human Neuroscience, 6.

Timmermans, B., Schilbach, L., Pasquali, A., & Cleeremans, A. (2012). Higher order thoughts in action: consciousness as an unconscious re-description process. Philosophical Transactions of the Royal Society B: Biological Sciences, 367(1594), 1412-1423.

Ullsperger, M., Harsay, H. A., Wessel, J. R., & Ridderinkhof, K. R. (2010). Conscious perception of errors and its relation to the anterior insula. Brain Structure and Function, 214(5-6), 629-643.

Veen, V. V., & Carter, C. S. (2006). Conflict and cognitive control in the brain. Current Directions in Psychological Science, 15(5), 237-240.

Wessel, J. R. (2012). Error awareness and the error-related negativity: evaluating the first decade of evidence. Frontiers in Human Neuroscience, 6, 88.

Wessel, J. R., Danielmeier, C., & Ullsperger, M. (2011). Error awareness revisited: accumulation of multimodal evidence from central and autonomic nervous systems. Journal of Cognitive Neuroscience, 23(10), 3021-3036.

Zacharopoulos, G., Binetti, N., Walsh, V., & Kanai, R. (2014). The effect of self-efficacy on visual discrimination sensitivity. PloS one, 9(10), e109392.