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Special Focus on Emotion

Opinion
Forming Beliefs: Why Valence Matters

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One of the most salient attributes of information is valence: whether a piece of news is good or bad. Contrary to classic learning theories, which implicitly assume beliefs are adjusted similarly regardless of valence, we review evidence suggesting that different rules and mechanisms underlie learning from desirable and undesirable information. For self-relevant beliefs this asymmetry generates a positive bias, with significant implications for individuals and society. We discuss the boundaries of this asymmetry, characterize the neural system supporting it, and describe how changes in this circuit are related to individual differences in behavior.

Trends

Humans update self-relevant beliefs to a greater extent in response to good news than bad news.

This asymmetry is mediated by differential neural representation of desirable and undesirable estimation errors.

The extent of this asymmetry varies with age and mental health.

Biased Beliefs

How does our mind integrate information to form beliefs about reality? What are the rules by which information is transformed into beliefs? This problem has occupied scholars for decades. Most classic theories in economics [1], machine learning [2–4], and psychology [5,6] assume that agents gather and integrate information in a manner that will result in a relatively accurate representation of reality. The assumption is that such representations would help people make predictions that can guide action towards rewards and away from harm.

However, examining people's beliefs about themselves and their future reveals systematic biases [7–14]. Most humans, for instance, hold a **superiority illusion** (see Glossary) by which they believe they are better and more skilled than most other people [9,15–18]. The majority also hold **unrealistic optimism** – the tendency to overestimate the likelihood of encountering positive future events and underestimate the likelihood of encountering negative events [19–25]. For example, a classic study reported that students estimated they were 13% more likely to receive an award than the other students in the class, 32% less likely to suffer lung cancer, and 49% less likely to become divorced than their peers [19]. While some have claimed that the superiority illusion and unrealistic optimism reflect valid beliefs [26], this seminal study [19], as well as others (see [27] for review), describe beliefs that are impossible and/or proven to be false (e.g., [28]).

How Can Such Systematic Errors in Beliefs Be Accounted For?

We argue that these observations reveal a fundamental property of learning. Namely, that desirable and undesirable information is used differently to alter self-relevant beliefs, resulting in systematic biases. Below we consider recent behavioral, computational, biological, and developmental evidence suggesting that humans hold a valence-dependent asymmetry in how they update self-relevant beliefs. All else being equal, undesirable information is under-weighed relative to desirable information, a phenomenon that is not easily accounted for by traditional models of learning (also see [29]).

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We consider the boundaries of this asymmetry, whether it may be adaptive, whether similar phenomena are observed in other species, and how it alters with development (for open questions and future directions, see Outstanding Questions).

Asymmetric Updating Generates Biased Beliefs

A growing literature indicates that beliefs are more readily updated in response to information that calls for adjusting one's views in a positive direction than a negative direction – also known as **asymmetric updating**. For example, subjects are more likely to update beliefs when receiving 'good news' regarding their likelihood of encountering aversive events (such as learning their likelihood of being a victim of credit card fraud is lower than they thought – also known as a positive **estimation error**) than when receiving 'bad news' (learning that their likelihood is greater than they thought – also known as a negative estimation error) [30] (Figure 1). The same pattern emerges when people receive desirable and undesirable information about their financial prospects [31], or feedback about their intellectual abilities [32,33], personality [34] and physical traits [32] (Box 1). In all these cases, desirable information is integrated into prior beliefs more readily than undesirable information, resulting in positively biased beliefs. The difference is robust and is observed in approximately 80% of the population, regardless of country, and gender [30,35–38].

What Underlies Asymmetric Updating?

Perhaps people more readily integrate good news into their beliefs than bad news, not because good news is more desirable but because it is more consistent with their priors. In other words, maybe asymmetric updating simply reflects a **confirmation bias**? This is not the case; participants more readily update their beliefs when they receive good news than bad news even when good news contradicts their prior beliefs such as when a person who believes they hold below average IQ learns they had received above average scores ([32]). Nor can asymmetric updating be explained by positively skewed priors. Studies that elicit participants' full distribution of a prior belief show that subjects' posteriors diverge significantly from what would be expected from a Bayesian agent following bad news, but converge with Bayesian posteriors following good news [32]. Although participants place full weights on their priors, they still underweight negative evidence relative to positive evidence [33] and they do so even when incentivized to report accurate beliefs [32].

Asymmetric Use, and Neural Representation of, Estimation Errors

We have shown that asymmetric updating results from differential use of positive and negative estimation errors [30]. Estimation errors quantify the difference between existing beliefs and new information [30] (Figure 1). These are distinct from **prediction errors**, which quantify the difference between expected outcomes and tangible outcomes, such as a reward or loss, obtained when performing an action [4,39,40] (see section on Reinforcement Learning Tasks below). When receiving information that is better than expected people update their belief in proportion to the error made. However, they are less likely to do so following information that is worse than expected [30,36,41] (Figure 1).

Imprecise weighting of negative estimation errors is related to a relative failure to encode negative estimation errors in frontal brain regions, particularly the inferior frontal gyrus (IFG) and medial frontal cortex (MFC), compared to adequate coding of positive estimation errors [30] (Figure 1). Across individuals, the asymmetry in neural representation of estimation errors is predictive of subsequent failure to alter beliefs in response to undesirable information [30]. People with balanced updating of beliefs, such as mildly depressed individuals [41] and people with low trait optimism [30], show balanced neural representation of estimation errors.

Glossary

Asymmetric updating (positive): adjusting beliefs to a greater extent in response to good news than bad news.
Confirmation bias: the tendency to adjust beliefs to a greater extent in response to information that is consistent with our prior belief than to information that is inconsistent.
**Estimation error:** the difference between a belief regarding the likelihood of an event and information regarding the likelihood of that event.
Overconfidence: the tendency to overestimate our own skills and/or knowledge.
Prediction error: the difference between the expected outcome and experienced outcome.
Superiority illusion: the tendency of the majority of people to believe they are better and more skilled than the majority of people.
Unrealistic optimism: overestimating the likelihood of future positive events and/or underestimating the likelihood of future negative events.

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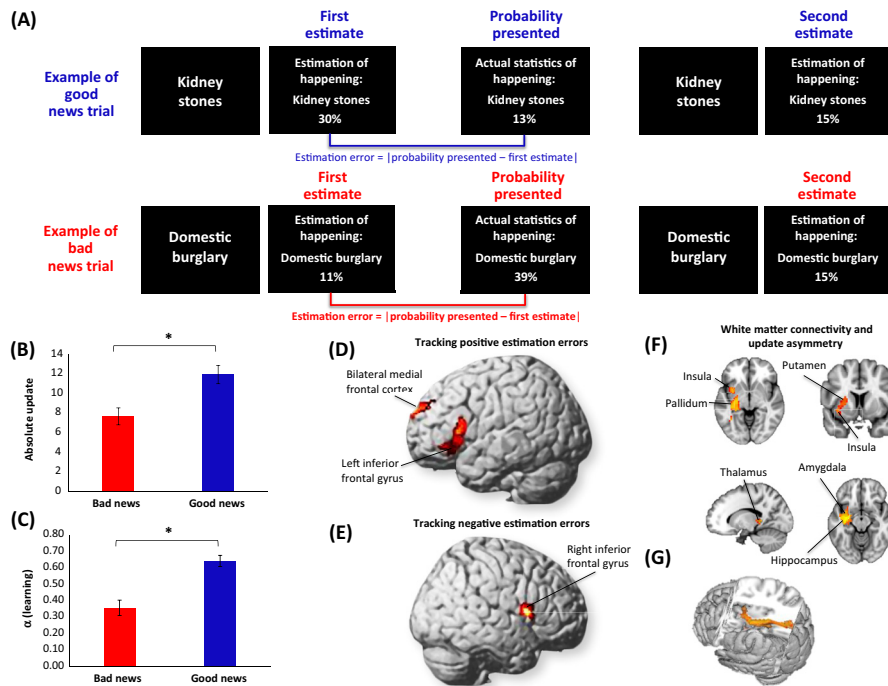
Trends in Cognitive Sciences

Figure 1. Belief Update Task: Brain and Behavior. To test for asymmetric belief formation and quantify its extent we have recently developed the belief update task. (A) Participants are presented with approximately 80 different life events and are asked to estimate their likelihood of experiencing each event. They are then presented with the average likelihood of the event occurring to someone like them and are asked to re-estimate their likelihood. (B) Participants adjust their beliefs to a greater extent when they receive good news (i.e. that a negative event is less likely to occur than expected) compared to when they receive bad news (i.e., that a negative event is more likely to occur than expected) [30]. The results are evident both when the re-estimate is elicited shortly after information presentation [30] and when elicited while information is still on screen [38], thus eliminating the possibility that the results are mediated by memory differences for the information. Indeed, memory for the information provided does not differ for good and bad news, and the results hold when controlling for participants' prior estimates, past experience, and other stimuli specific features. (C) The use of separate learning parameters, one for good news (α_G) and one for bad news (α_B), leads to a better fit with the data than a model using a single learning parameter. The learning parameter (α) is derived from this equation: second estimate = first estimate + α(estimation error), where estimation error is the difference between the first estimate and the information given. The graphs in (B,C) are generated from the combined data of 30 healthy participants across two studies [30,41]). (D) Estimation errors for good news correlate with blood oxygenation level-dependent (BOLD) signal in the left inferior frontal gyrus (IFG) and the medial frontal cortex (MFG). Figure adapted from [30]. (E) Estimation errors for bad news correlate negatively with BOLD response in the right IFG. Figure adapted from [30]. (F,G) Diffusion tensor imaging reveals that individuals with greater positive update bias have stronger white matter connectivity between the left IFG and left pallidum, left insula, left putamen, left amygdala, left hippocampus, and left thalamus. Figure adapted from [42].

Asymmetric information integration, however, is not explained by function of frontal regions alone. Instead, recent evidence suggests that it is the interaction between these frontal regions and regions involved in emotion and value processing that underlie asymmetric learning [42]. In particular, across individuals increased white matter connectivity between the left IFG (which is involved amongst others in error-monitoring [43], encoding evidence relative to prior knowledge [44], reversal learning [45], risk prediction-error [46] and inhibition [47]) and the left amygdala, putamen, pallidum, thalamus, and insula (which all play a role in emotion, valuation, and motivation) are associated with greater updating asymmetry (Figure 1 F,G). This is characterized both by an increased tendency to alter beliefs in response to desirable information and a reduced tendency to alter beliefs in response to undesirable information [42]. Interfering with the activity in this system by administering TMS to the left IFG abolishes the asymmetry in updating [48]. We speculate that increased white matter connectivity within the

Box 1. Explaining Valence-Dependent Updating with Normative Models?

To examine whether people conform to Bayesian updating when confronted with desirable and undesirable information the following experiment was conducted [32]. Groups of 10 participants were asked to rate each other on an attractiveness scale. Each participant was then asked to plot a histogram that represented their perceived likelihood of being rated overall as the most attractive in the group (position 1) to the least attractive in the group (position 10). On each trial a participant was told whether their overall rank was above or below another randomly selected anonymous participant. Hence participants could get good news (someone else in the group was rated less attractive than them) or bad news (someone else in the group was rated more attractive than them). Participants were then asked to redraw their belief histogram. Comparing participants' posteriors to those of a Bayesian agent showed that following good news subjects updated their beliefs in a normative, Bayesian, manner (R squared accounting for subjects' posterior with a Bayesian posterior was approximately 0.8), but less so following receipt of bad news (R squared ~0.5) (Figure IA,B). In another study [33] participants (n >2000) undertook an IQ test and were then asked to estimate the likelihood that they were in the top half of performers. After each estimate they received a noisy signal (correct with 75% probability) informing them whether they were in the top or bottom half of performers, and were then asked to re-estimate the likelihood that they were in the top half of performers. Participants' posteriors were more similar to that of a Bayesian agent following receipt of good news than bad news, although in general their updates were more conservative than a Bayesian. Both studies showed that asymmetric information integration cannot be accounted for simply by skewed priors.
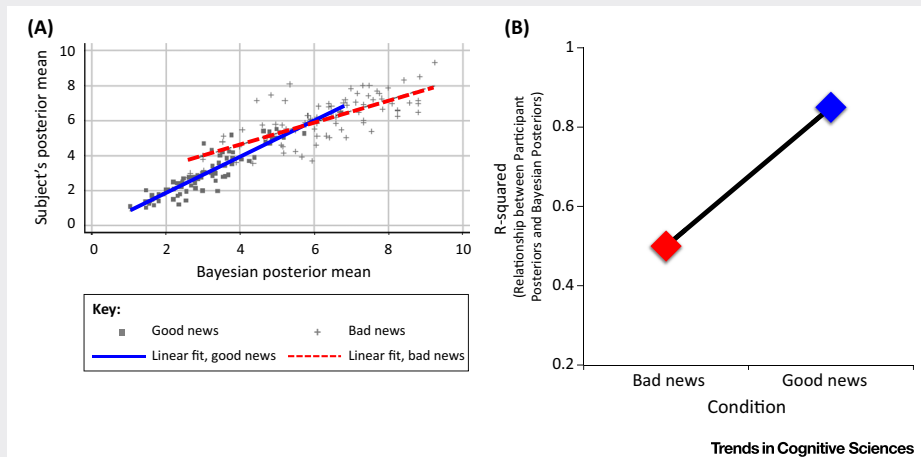

Figure I. Explaining Valence-Dependent Updating. Adapted from [32].

system described may indicate greater potential for structures within the system to communicate, and modulate information, allowing valance and motivation to be incorporated into the process of belief formation.

When Is Asymmetric Updating Observed? (Conditions and Boundaries)

Positively biased asymmetric integration of information is most likely to be observed when two conditions are met: beliefs are motivated and information is ambiguous.

Motivated Beliefs

Beliefs have value in and of themselves, in the sense that they are 'consumed', with positive beliefs eliciting positive feelings, and thus having positive utility, and negative beliefs eliciting negative feelings, and having negative utility [49,50]. People are thus motivated to maintain a positive optimistic view of themselves, their circumstances, and their future, and to disregard negative information. By contrast, when there is no intrinsic or external advantage for holding a belief, or when the advantage is relatively small, an asymmetry in updating may be less apparent. It has been shown that learning asymmetries can be explained with a Bayesian model, if that model accounts for the fact that agents derive utility from beliefs *per se* [33].

Outcomes Are Open to Interpretation

A positivity bias in learning is more likely to be observed when information is ambiguous and open to interpretation. For instance, a larger positivity bias in belief updating is observed when people receive information on how others rated their appearance than when updating beliefs about self-intelligence after receiving IQ scores [32]. Presumably, attractiveness ratings are more easily viewed as subjective, and thus negative feedback is more readily open to interpretation. This is consistent with the observation that people are more likely to perceive themselves as above average on ambiguous traits [51]. On the other hand, when outcomes are relatively unambiguous, such as experienced events (e.g., hearing loss experienced rather than information about the likelihood of hearing loss provided), positive asymmetry is less likely [52].

Reinforcement Learning (RL) Tasks

RL studies show that people learn differently from positive and negative prediction errors [53–56]. Models that include two separate learning rates for positive and negative prediction errors often outperform those with a single rate [53,56,57]. These studies support the notion that different rules and mechanisms underlie learning from relatively desirable and undesirable outcomes.

However, learning rates in response to positive outcomes are larger than in response to negative outcomes only when the above two constraints are met. For example, in one study participants were presented with a virtual slot machine [58]. They were told the slot machine could be in a positive mode, in which case playing it is more likely to result in a reward, or in a negative mode, in which case playing it is more likely to result in a loss. The participants were required to play the slot machine and asked after each trial to guess which mode the slot machine was tuned to. This is a case where (i) participants are motivated to believe the slot machine is in a positive mode because a positive mode results in greater rewards, and (ii) outcomes are ambiguous in relation to that belief – a positively tuned slot machine could still result in a loss. Findings show that participants update their beliefs regarding the mode of the slot machine to a greater extent in response to positive outcomes than negative outcomes.

Compare the above experiment to a case in which participants are presented with two slot machines X and Y, and need to learn which of the two will provide the most rewards. The participant may believe at first that X is better, select it, and experience a loss. This outcome is ambiguous in relation to the belief that X is better than Y. However, the participant has no motivation to hold on to that belief. Participants are only motivated to believe they will win. In relation to that belief, the outcome is not ambiguous – the loss is certain and undesirable. Studies employing setups analogous to this do not find greater learning rates in response to positive prediction errors relative to negative prediction errors [53,56,57].

Adaptive Function

Could positively biased information integration be an adaptive strategy? On the one hand, ignoring unwanted news may be suboptimal, leading to an underestimation of risk and reduced likelihood of precautionary action. The tendency to discount evidence-based warnings leads to over-optimism and over-confidence, which in turn have been blamed for a host of disasters including war [59], overly aggressive medical decisions [60], ill-preparedness in the face of natural catastrophe [61], and financial collapse [62]. Moreover, positively biased views of the self can lead to error and cost, as shown for **overconfident** CEOs (for review, see [63]) and overconfident stock traders [64].

Some scholars have concluded that, although some negative consequences for over-optimism and over-confidence can be observed, on balance the adaptive consequences outweigh them [65]. In particular, positive expectations reduce stress and lead to better physical and mental

health [66–68]. People holding positive expectations, even when mildly unrealistic, live longer and recover more quickly from illness [69–71]. Furthermore, both balanced information integration and reduced optimism have been observed in clinically depressed individuals [35,41,72]. Second, positive expectations can act as motivation for productivity and exploration, increasing innovation and success in many domains [73–76]. If self-efficacy beliefs were merely to mirror what people could reasonably accomplish, people would seldom fail – but neither would they mount the extra effort required to go beyond ordinary performance [77].

Computational simulations indicate that biased agents outperform non-biased agents in attaining rewards, but only under particular circumstances. Specifically, 'overconfident' agents, who overestimate their likelihood of attaining rewards and avoiding harm, do better than others in environments where costs are not significantly greater than potential gains [78]. This is because, under uncertainty, biased agents would claim resources (i.e., equivalent to a spouse or a job) they could not otherwise attain as better but less optimistic competitors may walk away from the fight. Moreover, they are less likely to turn away from conflicts they could objectively win. However, in environments where potential harm is considerably greater than potential reward, the model shows the bias to be disadvantageous [78]. We emphasize that the discussion is of a bias. This means that in environments where resources are greater than harm a biased individual will still overestimate the resources and underestimate the harm.

These simulations raises the intriguing possibility that the bias in belief formation may fluctuate in response to acute changes in the environment in a way that may be optimal. That is to say, in relatively safe environments biased information integration may be prominent, leading to biased expectations, but in environments rife with threat a more-balanced approach to information integration may be evident, which can promote less biased beliefs and more caution.

Evidence in Non-Human Animals

While asymmetric updating has not been tested for in non-human animals, positively biased expectations have been observed, as well as their fluctuations in response to environmental change. Studies in starlings [79], rats [80], chicks [81], and pigs [82] indicate that under uncertainty, animals show a tendency to interpret ambiguous stimuli as predictive of positive outcomes unless they have been exposed to a stressor. For example, in one study [82] pigs were trained to approach a hatch in a training arena if a specific auditory tone was presented (a note on a glockenspiel) so as to receive a reward (an apple), but to stay away from the hatch if another auditory tone was presented (a dog-training clicker sound) to avoid an aversive outcome (a plastic bag waved in the pig's face). A novel tone was then introduced. The question was whether the pigs would approach the hatch, suggesting that they expected the new tone to indicate an upcoming reward, or stay away, indicating that they expected an aversive outcome. On 90% of the trials pigs would approach the hatch. However, this was only true of pigs housed in comfortable accommodation with ample space, straw, and objects to manipulate. Pigs housed in a barren environment showed no bias and approached the hatch about 50% of the time. Other studies have reported similar results in different species using variations of this paradigm that control for possible confounds, including the use of two rewards of different magnitude instead of one aversive outcome and one rewarding outcome, and two separable approach responses instead of a go/no-go design [79,83]. All show that animals are more likely to interpret ambiguous stimuli as indicative of a previously learned positive outcome if living in a relatively stress-free environment.

Whether these biases in non-human animals (particularly mammals) are precursors of those observed in humans is unknown (see Outstanding Questions). It seems likely that in some species (starlings for example) these biases have evolved independently, converging on a potentially useful trait.

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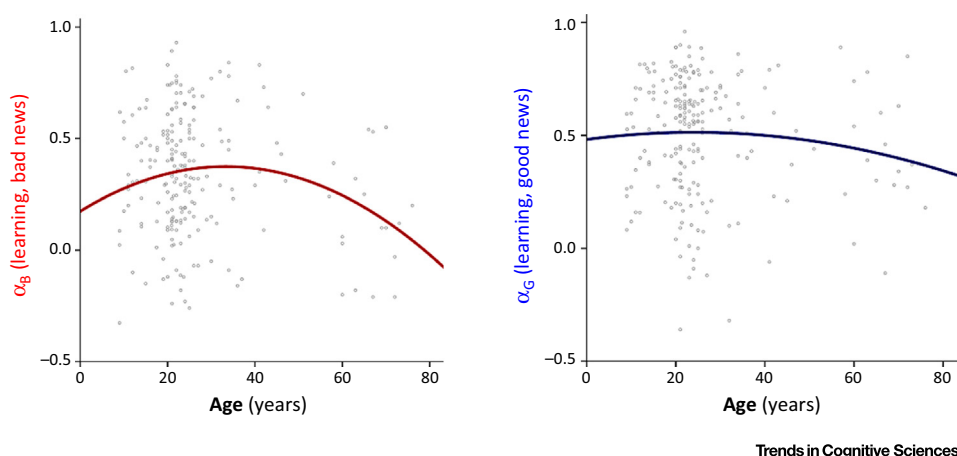
Figure 2. How Information Integration Alters with Age. Learning from bad news (α_B) changes with age following an inverse-U shape (quadratic) function; it is low in children and teenagers, peaks around middle age, and then starts to decline again. This pattern is not observed for learning of good news (α_G), which remains relatively stable over the lifetime. Figure includes data from [30,36,37,41].

Development

The asymmetry in information integration alters with age following a U-shaped function; the bias is large in children and teenagers (tested from the age of 9) [36] and drops slowly hitting its lowest point around middle age at which time it starts rising again [37]. By old age the bias reaches a magnitude roughly similar to that observed in early adolescence [36,37]. This pattern is driven by changes in how undesirable information is incorporated into beliefs. Specifically, while the ability to integrate unexpected good news into beliefs does not change significantly with age [36,37], the ability to integrate unexpected bad news follows an inverse-U shape (Figure 2). Children and teenagers show a relative impairment in their ability to accurately adjust beliefs in response to undesirable information [36]. This ability increases with age, peaking around mid-life, and then starts decreasing again [37] (Figure 2). The different developmental trajectories of how people learn from good and bad news support the notion that the two are mediated by partially separable mechanisms.

What causes these developmental changes in valence-dependent information integration is unknown. One possibility is that the pattern is related to brain changes. For example, it may reflect maturation of part of the neural system and subsequent decline of that same system [84–87]. Alternatively, the cause for the increase of learning from negative information in the first half of life can be independent of the decline thereafter (the latter is consistent with [88]) and/or explained by non-physiological environmental factors.

Concluding Remarks

Humans integrate information into self-relevant beliefs asymmetrically based on the desirability of the information at hand. Positive and negative errors in prediction and estimation are coded differentially by the brain [30,41,89] and are used unequally to alter beliefs [30,53–56], possibly guided by different rules [32]. Furthermore, the ability to alter beliefs in response to desirable and undesirable information follow different developmental trajectories [36,37], further supporting the notion that the two processes are dissociated. For self-relevant beliefs, where people are motivated to hold positive views, a valence-dependent asymmetry in how people use favorable and unfavorable information results in positively biased views, such as unrealistic optimism [30] and the illusion of superiority [34]. Although such views are biased, they are not necessarily suboptimal. The positive effects of these illusionary beliefs on our affective state [49,50,90], health [68], and motivation [91,92] may be adaptive, on balance (see [93,94] for reviews).

Outstanding Questions

Genetics. Do genetic factors account for individual differences in asymmetric learning? There is good reason to hypothesize that genes related to dopaminergic function will predict individual differences in asymmetric belief formation. First, enhancing dopaminergic function via the administration of L-DOPA (L-3,4-dihydroxyphenylalanine) reduces learning from undesirable information [95]. Second, within reinforcement-learning tasks, individual differences in learning from positive and negative prediction errors has been respectively related to genetic polymorphisms of the *DARPP32* (dopamine- and cAMP-regulated phosphoprotein 32, also known as PPP1RB) and *DRD2* (dopamine receptor D2) genes [54,96]. *DARPP32* encodes an intracellular protein that is concentrated in the striatum. This protein, phosphatase 1, is inhibited when phosphorylated by dopamine receptor D1 stimulation, thus enabling corticostriatal synaptic plasticity. *DRD2* alleles determine dopamine receptor D2 affinity; this is primarily expressed by striatopallidal medium spiny neurons that are sensitive to dips of dopamine below baseline. In addition, a polymorphism of the *COMT* (catechol-*O*-methyltransferase) gene, which is associated with individual differences in prefrontal dopamine function, has been shown to be related to the in/ability to learn from new information that does not fit with a subject's prior beliefs [97]. *COMT* encodes an enzyme that breaks down extracellular dopamine [98,99], modulating dopamine levels and D1 receptor availability in prefrontal cortex [100–102], thus possibly influencing striatal activity indirectly by affecting prefrontal neurons that project to striatum [103]. An open question is whether the same genetic polymorphisms also predict learning from positive and negative estimation errors for motivated beliefs.

Development. Is asymmetric information integration present in very young children and infants? Are there early experiences that are necessary for the asymmetry to be present or absent? Do environmental factors play a pivotal role in the development of the asymmetry, and if so which and when? Do biological factors play a role? How do these factors interact in shaping the developmental trajectory of valenced information integration?

Evolution. How might have asymmetric information integration arisen and evolved through phylogenetic processes? Are the positivity biases observed in non-human animals [79,82] related to asymmetric updating?

Boundaries. We have suggested that asymmetric updating is less likely to be observed when beliefs are not motivated and when outcomes are unambiguous in relation to those beliefs. A systematic investigation of these boundaries has yet to be conducted.

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