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Research report

The influence of task complexity and information value on feedback processing in younger and older adults: No evidence for a positivity bias during feedback-induced learning in older adults

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HIGHLIGHTS

- Processing of negative but not positive feedback might be impaired in old age.
- We found no hint of such a positivity bias in feedback processing in older adults.
- Older adults learned worse when information value of negative feedback was reduced.
- Thus, older adults can process negative feedback effectively when it is relevant.

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ABSTRACT

Humans flexibly adapt their behavior using feedback from their environment. This ability is impaired in old age, but recent research suggests this mainly concerns processing of negative feedback and that positive feedback might be spared. The aim of this study was to test this idea of an age-related positivity bias against the possibility of a strategic focus on relevant feedback due to limited processing resources in old age. For this purpose, 17 younger (aged 19 to 28 years) and 18 older (aged 69 to 79 years) adults performed a learning task in which they learned the correct response to a stimulus via feedback. Learning relevance was manipulated by varying the informational value of positive and negative feedback. To manipulate available processing resources, the task was conducted under two difficulty levels. Our results showed no hint of a positivity bias in older adults. On the contrary, we found that they learned worse when the information value of the negative feedback was reduced. This is in line with the idea that the positivity effect in older adults reflects a strategic change in motivation, i.e., older adults preferably process positive information if they have a choice, but they can process negative information as effectively when it is relevant for the task at hand. For younger adults, negative feedback seemed to be more important, too, because it modulated later higher-order feedback processing as indexed by the P3b. They showed reduced working memory updating and a more frontal P3b distribution indicating a higher processing effort in conditions in which the information value of negative feedback was reduced.

1. Introduction

Feedback processing is an important prerequisite to flexibly adapt our behavior to specific situational demands. By feedback from our environment, we learn which behavior is appropriate or leads to a desired goal. In old age, this ability is still very important to adapt to changes in our environment, e.g., an increased use of complex digital interfaces and automation. Unfortunately, many studies have demonstrated that older adults show impaired feedback processing and thus impaired learning (e.g., Marschner et al., 2005; Mell et al., 2005; Schmitt-Eliassen et al., 2007; Weiler et al., 2008). However, other studies suggest that older adults show a positivity bias (for a review, see Carstensen and DeLiema, 2018), i.e., they preferably process positive information and thus impairments are mainly found in learning from negative feedback (e.g., Eppinger et al., 2008). The aim of the present study was to examine whether there is a positivity bias during feedback-induced learning and whether older adults are impaired in learning from negative but less so from positive feedback.

In recent years, feedback processing has been intensively examined in reinforcement learning tasks. This research has shown that feedback processing depends on the mediofrontal cortex, especially the anterior cingulate cortex (ACC), which predicts the likely outcomes of events

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and signals when these expectations were incorrect (e.g., Alexander and Brown, 2011; Holroyd and Coles, 2002). The resulting reinforcement learning signals heavily rely on intact dopaminergic functioning (Frank et al., 2004; Holroyd and Coles, 2002; Schultz, 2002).

Feedback processing can be examined online by means of event-related potentials (ERPs). With this method, it has been found that feedback is evaluated in several consecutive steps. There is an initial, fast processing step indexed by the feedback-related negativity (FRN). The FRN is measured over fronto-central brain areas after subjects receive feedback (e.g., Ferdinand et al., 2012; Gehring and Willoughby, 2002; Holroyd and Coles, 2002; Miltner et al., 1997; Opitz et al., 2011), reflecting the detection of an event that is worse than expected, and is generated in the ACC (e.g., Ferdinand and Opitz, 2014; Gehring and Willoughby, 2002; Miltner et al., 1997; Ullsperger and von Cramon, 2001). The FRN can be measured in a peak-to-peak fashion reflecting the size of the expectancy violations (e.g., Ferdinand et al., 2012). When measured as mean amplitude FRN, there usually is a general amplitude difference with more negative amplitudes for negative than positive feedback reflecting the processing of the feedback's valence (e.g., Holroyd and Coles, 2002). Additionally, there is a later evaluation process reflected in the P3b. The P3b has been linked to working memory updating after unexpected, surprising events (for a review see Polich, 2004, 2007) and to the evaluation of task relevance (e.g., Mecklinger et al., 1994; Ruchkin et al., 1990).

Previous studies have demonstrated that older adults generally show impaired learning from feedback or rewards (Marschner et al., 2005; Mell et al., 2005; Schmitt-Eliassen et al., 2007; Weiler et al., 2008) and a reduced FRN (Bellebaum et al., 2011; Eppinger et al., 2008; Eppinger et al., 2013; Hämmerer et al., 2010; Mathalon et al., 2003; Mathewson et al., 2005; Mell et al., 2009) as compared to younger adults. According to Nieuwenhuis et al. (2002), these age-related impairments in feedback-induced learning result from a weakened reinforcement learning signal from the dopamine system to the ACC. In line with this idea, it has been shown that aging is associated with pronounced changes in the mesencephalic dopamine system and in neural areas that receive input from this system, like the prefrontal cortex (Bäckman et al., 2000, 2006; Raz et al., 2005). Dopaminergic functioning has also been linked to age-related impairments in working memory. For instance, Erixon-Lindroth et al. (2005) found that dopamine transporter density in the caudate nucleus and putamen explained the variation in working memory performance over and above age (for a review on the relationship between age, dopaminergic and cognitive functioning, see Bäckman et al., 2006). In line with this, age-related differences in P3b amplitude and topography have been found during feedback processing (e.g., Ferdinand and Kray, 2013). Thus early and later phases of feedback processing seem to be impaired in old age.

Recently, several studies have argued that older adults might be impaired mostly during processing and learning from negative feedback due to an age-related positivity bias. For instance, Eppinger et al. (2008) found that older adults FRN after negative feedback was reduced reflecting age-related impairments in processing negative feedback. However, they also found that the ERP in the FRN time range changed with increasing learning only after positive, not after negative feedback. They concluded that older adults rely more on positive feedback during learning because processing negative feedback is impaired (see also Pietschmann et al., 2011). Similarly, Di Rosa et al. (2017) found worse performance in the Iowa Gambling Task with increasing age. At the same time, P3 amplitude was reduced selectively after negative feedback in older adults. They concluded that due to impairments in processing of negative feedback, older adults were less willing to shift their attention from positive to negative information. Fernandes et al. (2018) found that older adults displayed the same pattern of feedback processing in the FRN as younger adults in conditions of a gambling task where they could gain points, i.e., they showed a larger FRN for unfavorable feedback. However, they showed impairments in conditions where they could loose points. These finding could be interpreted in terms of a positivity effect. In line with this idea, Samanez-Larkin et al. (2007) showed reduced striatal and insular activation to potential losses, but not to potential gains, in older as compared to younger adults. In contrast to these findings, there are also studies suggesting that older adults learn better from negative than positive feedback (cf. Frank and Kong, 2008; Hämmerer et al., 2010), that there is no difference between learning from positive and negative feedback (cf. Simon et al., 2010), or that older adults show a positivity bias when learning by observation of others, but not during actively learning from feedback themselves (cf. Bellebaum et al., 2012). Thus, all in all, evidence concerning an age-related positivity bias during learning is rather mixed.

In one of our own studies (Ferdinand and Kray, 2013), we examined feedback processing by means of a time estimation task. We found that younger and older adults both clearly showed an early detection of expectancy violations in the form of the FRN and a later feedback evaluation phase as indexed by the P3b. For the early detection of expectancy violations, older adults showed the same pattern of results as younger ones: The FRN was larger for unexpected (positive and negative) feedback than for expected feedback. Thus, the monitoring system of older adults processed expectancy violations in the same manner as that of younger adults. We only found marginally smaller FRNs in older adults in general, i.e., to all types of feedback, showing a slightly reduced reactivity of the monitoring system in older adults. Larger age effects, however, were found for the later stage of feedback processing related to working memory updating after unexpected events as reflected in the P3b. In younger adults, unexpected negative feedback elicited a larger P3b than expected feedback and additionally, unexpected positive feedback elicited a larger P3b than the equally unexpected negative feedback. Thus, younger adults showed more working memory updating after unexpected than expected feedback (effect of unexpectedness), but also more updating after positive feedback probably because this type of feedback was especially informative in this task (effect of task relevance). In contrast, in older adults only unexpected positive feedback elicited a larger P3b, while unexpected negative and expected feedback did not differ. We argued that this pattern of results does very likely not reflect a positivity bias because younger as well as older adults processed positive feedback more strongly. Instead, we speculated that, probably due to their reduced working memory capacity, older adults were not able to process all three types of feedback in this task but instead had to focus on the most relevant feedback type, i.e., the unexpected positive feedback. By this, they seemed to strategically favor the processing of task relevance over that of unexpectedness. This idea was in line with a more frontal topography of the P3b in older adults which is often interpreted in terms of a compensatory mechanism (Adrover-Roig and Barceló, 2010; Reuter-Lorenz and Lustig, 2005): Older adults have to recruit additional frontal brain areas as compared to younger adults to be able to solve the same task.

The present study aimed at further examining this issue and testing the possibilities of an age-related positivity bias and an age-related focus on task relevance due to working memory impairments against each other. For this reason, younger and older adults performed a probabilistic learning task in which they were to learn the correct response to a stimulus by means of feedback. The feedback's relevance for learning was manipulated by varying the informational value of the feedback stimuli. There were trials in which the feedback was valid in 100% of the cases, and there were trials in which either the positive or the negative feedback stimuli were less useful for learning because they were uninformative in 20% of cases, respectively (see Fig. 1b). Our hypotheses were that if a positivity bias is at work in older adults, feedback processing (as reflected in the FRN and P3b) and learning (as reflected in decreasing reaction times and increasing response accuracy over the course of the experiment) should be impaired more when the informational value of positive feedback is reduced as compared to when the informational value of negative feedback is reduced. In

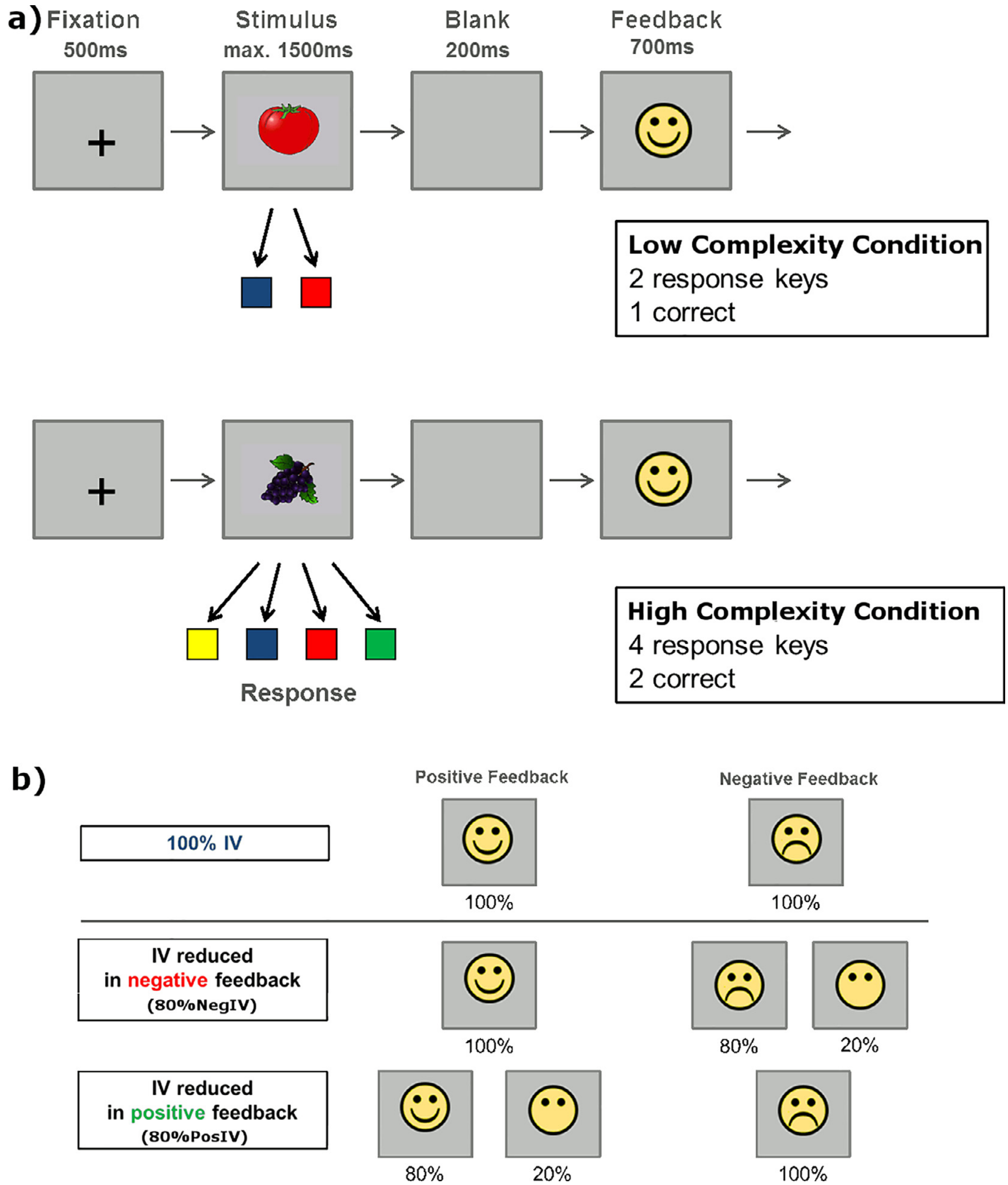

Fig. 1. a) Trial procedure including timing and response keys for the low and high complexity task conditions. b) Feedback stimuli in the three IV conditions. In the 100% IV condition, feedback was informative in 100% of cases. In the 80% IV conditions, IV of the feedback was reduced by exchanging either the positive (80% PosIV condition) or the negative (80% NegIV condition) informative feedback by uninformative feedback which conveyed no information about whether the response had been correct or incorrect (a smiley without a mouth).

contrast, if older adults show a task relevance focus, they should adapt to the informational value conditions, i.e., when the relevance of the positive feedback is reduced by exchanging a proportion of positive feedback by uninformative feedback, processing of positive feedback should be reduced while processing of negative feedback should be enhanced. The opposite should be the case in the condition in which negative feedback is exchanged by uninformative feedback. For younger adults, we assumed to find better and faster learning over the course of the experiment than in older adults and the presence of a relevance focus. Because earlier studies using similar probabilistic learning designs have shown that participants seem to rely more on negative feedback in this task (e.g., Frank et al., 2005), the 100% validity condition serves as a baseline against which the effects of a potential positivity bias or task relevance effect will be tested.

Additionally, to manipulate working memory demands, the task was conducted under two difficulty levels. There were learning blocks in which the participants had to find out one correct response for a specific stimulus out of two possible responses (low complexity task condition) and there were blocks in which they had to find out two correct responses out of four possible ones (high complexity task condition; see Fig. 1a). The idea behind this was that if the positivity bias or the task relevance effect are strategic effects that are applied under circumstances with reduced processing resources, these effects should be more prominent in older adults due to their limited working memory capacity and also under more demanding task conditions (possibly even in younger adults).

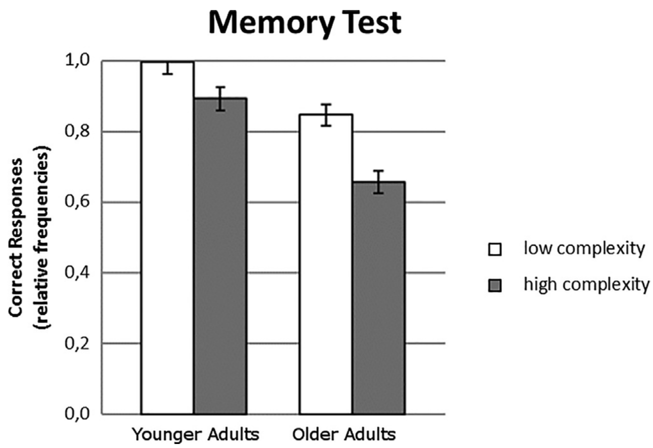

Fig. 2. Relative frequencies of correct stimulus-response assignments in the memory tests. Error bars denote the standard error of the mean.

2. Results

2.1. Behavioral results

2.1.1. Memory test

An ANOVA with the factors Age Group (younger, older) and Task Complexity (low, high) was conducted for the relative frequency of correctly remembered stimulus-response assignments in the memory tests after the learning blocks. This analysis revealed that younger participants remembered more stimulus-response assignments than older ones (F(1,33) = 28.3, $p < .001$, $\eta_p2 = 0.46$) and all participants remembered more in the low complexity condition of the task (F(1,33) = 31.2, $p < .001$, $\eta_p2 = 0.49$; see Fig. 2).

2.1.2. Accuracy

An ANOVA with the factors Age Group (younger, older), Task Complexity (low, high), Quarter (1 vs. 2, 2 vs. 3, 3 vs. 4), and the two planned contrasts on IV reduction (100% IV vs. 80% IV) and IV Valence (80% PosIV vs. 80% NegIV) on response accuracy revealed main effects of Age Group (F(1,33) = 8.9, $p < .01$, $\eta_p2 = 0.21$) and Task Complexity (F(1,33) = 32.0, $p < .001$, $\eta_p2 = 0.49$), significant comparisons between Quarter 1 and 2 (F(1,33) = 107.9, $p < .001$, $\eta_p2 = 0.77$), Quarter 2 and 3 (F(1,33) = 50.6, $p < .001$, $\eta_p2 = 0.61$), and Quarter 3 and 4 (F(1,33) = 5.9, $p < .05$, $\eta_p2 = 0.15$), and significant interactions between Task Complexity and Quarter 1 vs. 2 (F(1,33) = 6.2, $p < .05$, $\eta_p2 = 0.16$) and Task Complexity and Quarter 3 vs. 4 (F(1,33) = 6.4, $p < .05$, $\eta_p2 = 0.16$).

The main effect of Age Group was due to higher accuracy rates in younger than older adults and did not interact with any of the other factors. The interactions between Task Complexity and Quarter, were due to increasing accuracy over the quarters in the low (1 vs. 2: F(1,34) = 81.7, $p < .001$, $\eta_p2 = 0.71$; 2 vs. 3: F(1,34) = 8.0, $p < .01$, $\eta_p2 = 0.19$; 3 vs. 4: F(1,34) = 13.0, $p < .01$, $\eta_p2 = 0.28$) and the high complexity condition (1 vs. 2: F(1,34) = 30.4, $p < .001$, $\eta_p2 = 0.47$; 2 vs. 3: F(1,34) = 37.9, $p < .001$, $\eta_p2 = 0.53$; 3 vs. 4: $p = .66$) with larger differences between the low and the high complexity condition in later quarters, as can be inferred from effect sizes (1: F(1,34) = 11.9, $p < .01$, $\eta_p2 = 0.26$; 2: F(1,34) = 23.2, $p < .001$, $\eta_p2 = 0.41$; 3: F(1,34) = 19.2, $p < .001$, $\eta_p2 = 0.36$; 4: F(1,34) = 28.1, $p < .001$, $\eta_p2 = 0.45$). These results reflect slower learning and an earlier and lower plateau in the high complexity task condition (see Table 2 and Fig. 3a).

2.1.3. Reaction times

The same ANOVA with factors Age Group, Task Complexity, the planned contrasts of Quarter, and the planned contrasts of IV Reduction and IV Valence was computed for reaction times and revealed a main effect of Age Group (F(1,33) = 10.3, $p < .01$, $\eta_p2 = 0.24$), a significant comparison of Quarter 1 vs. 2 (F(1,33) = 24.6, $p < .001$, $\eta_p2 = 0.43$), and interactions between Age Group and Task Complexity (F(1,33) = 7.5, $p < .05$, $\eta_p2 = 0.19$), Age Group, Task Complexity, and Quarter 3 vs. 4 (F(1,33) = 9.1, $p < .01$, $\eta_p2 = 0.22$), Task Complexity, IV Reduction, and Quarter 3 vs. 4 (F(1,33) = 4.6, $p < .05$, $\eta_p2 = 0.12$), Task Complexity, IV Valence, and Quarter 3 vs. 4 (F(1,33) = 5.6, $p < .05$, $\eta_p2 = 0.14$), Age Group, Task Complexity, IV Reduction, and Quarter 2 vs. 3 (F(1,33) = 5.8, $p < .05$, $\eta_p2 = 0.15$), Age Group, Task Complexity, IV Reduction, and Quarter 3 vs. 4 (F(1,33) = 7.9, $p < .01$, $\eta_p2 = 0.19$), and Age Group, Task Complexity, IV Valence, and Quarter 3 vs. 4 (F(1,33) = 11.5, $p < .01$, $\eta_p2 = 0.26$). To dissolve these interactions, separate ANOVAs were conducted for each Age Group and level of Task Complexity.

For young adults in the low complexity condition, this ANOVA found a main effect for Quarter (1 vs. 2: F(1,16) = 7.1, $p < .05$, $\eta_p2 = 0.31$), reflecting decreasing reaction times from the first to the second quarter. Additionally, an interaction was obtained between IV Reduction and Quarter (3 vs. 4: F(1,16) = 4.9, $p < .05$, $\eta_p2 = 0.23$). However, follow-up tests did not reveal any significant differences between the third and fourth quarter in the 100%IV and 80%IV conditions (all p-values > 0.50). For older adults in the low complexity condition, we also found decreasing reaction times from the first to the second quarter (F(1,17) = 5.8, $p < .05$, $\eta_p2 = 0.26$) and an interaction between IV Valence and Quarter (3 vs. 4: F(1,17) = 5.4, $p < .05$, $\eta_p2 = 0.24$). This interaction was due to decreasing reaction times from the third to the fourth quarter in the 80%PosIV condition (F(1,17) = 6.7, $p < .05$, $\eta_p2 = 0.28$) as opposed to the 80%NegIV condition ($p = .57$). Post-hoc tests showed no significant differences in reaction times between the 80%NegIV and the 80%PosIV condition in the third ($p = .54$) and fourth quarter (p = .08).

In the high complexity condition, we found only a main effect of quarter in each age group, showing decreasing reaction times from the first to the second quarter in the younger adults (F(1,16) = 5.0, $p < .05$, $\eta_p2 = 0.24$) and from the second to the third quarter in the older adults (F(1,17) = 6.3, $p < .05$, $\eta_p2 = 0.27$; see Table 2 and Fig. 3b).

2.2. Feedback-locked ERPs

2.2.1. Peak-to-peak FRN

An ANOVA with the factors Age Group (younger, older), Task Complexity (low, high), Feedback Valence (positive, negative), and the two planned contrasts on IV reduction (100% IV vs. 80% IV) and IV Valence (80% PosIV vs. 80% NegIV) on peak-to-peak FRN at electrode FCz resulted in a main effect for Feedback Valence (F(1,33) = 10.1, $p < .01$, $\eta_p2 = 0.24$) and an interaction between Age Group and Feedback Valence (F(1,33) = 6.1, $p < .05$, $\eta_p2 = 0.16$). In young adults, the peak-to-peak FRN was larger for negative than positive feedback stimuli (F(1,16) = 10.0, $p < .01$, $\eta_p2 = 0.39$), while this effect was not significant in older adults (p = .47). The ANOVA on the peak-to-peak FRN did not reveal any significant effects or interactions including the factors complexity or IV (all p-values > 0.13; see Figs. 4 and 5).

2.2.2. P3b

An ANOVA with the factors Age Group (younger, older), Task Complexity (low, high), Feedback Valence (positive, negative), and the planned contrasts on IV reduction (100% IV vs. 80% IV) and IV Valence (80% PosIV vs. 80% NegIV) on P3b amplitude at Pz revealed main effects of Task Complexity (F(1,33) = 7.6, p < .01, $\eta_p^2 = 0.19$) and Feedback Valence (F(1,33) = 65.0, p < .001, $\eta_p^2 = 0.66$), and interactions between Age Group and Task Complexity (F(1,33) = 9.1, p < .01, $\eta_p^2 = 0.22$), Task Complexity and Feedback Valence (F(1,33) = 13.7, p < .01, $\eta_p^2 = 0.29$), Feedback Valence and IV

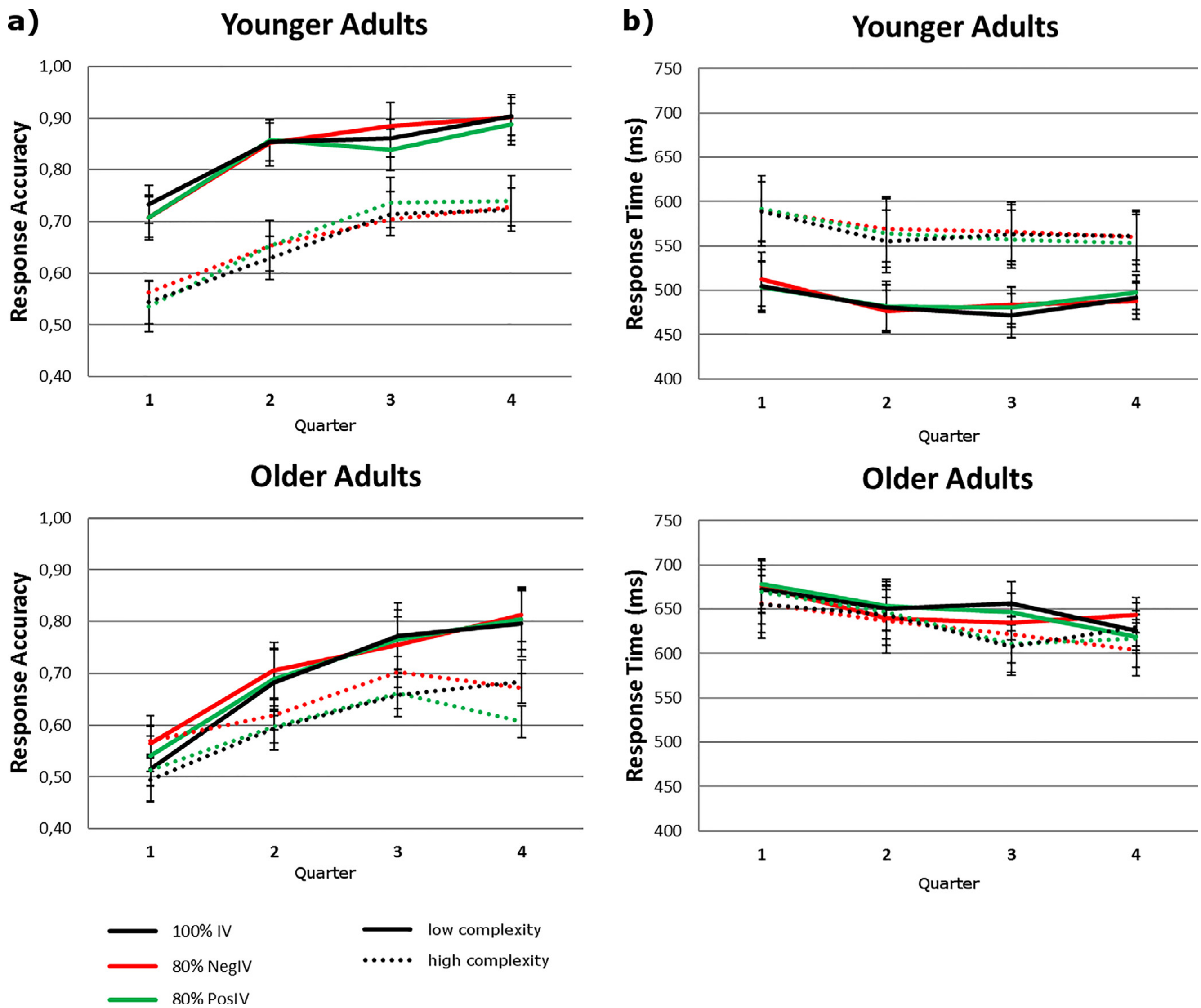

Fig. 3. a) Response accuracies and b) response times for younger and older adults across the quarters of the probabilistic learning task. Error bars denote the standard error of the mean.

Reduction ($F(1,33) = 7.9$, $p < .01$, $\eta_p^2 = 0.19$), and Age Group, Task Complexity, and Feedback Valence ($F(1,33) = 11.4$, $p < .01$, $\eta_p^2 = 0.26$).

The interaction between Task Complexity and Feedback Valence was due to the fact that the P3b was larger after negative than positive feedback in both complexity conditions (low complexity: $F(1,34) = 54.3$, $p < .001$, $\eta_p^2 = 0.62$; high complexity: $F(1,34) = 15.6$, $p < .001$, $\eta_p^2 = 0.32$) with larger effect sizes for the low complexity condition. Additionally, P3b amplitude was larger in the high than the low complexity condition after positive feedback ($F(1,34) = 24.6$, $p < .001$, $\eta_p^2 = 0.42$), but not after negative feedback ($p = .53$).

When dissolving the interaction between IV Reduction and Feedback Valence, we found that the P3b in both complexity conditions was larger after negative than positive feedback (low complexity: $F(1,34) = 54.3$, $p < .001$, $\eta_p^2 = 0.62$; high complexity: $F(1,34) = 15.6$, $p < .001$, $\eta_p^2 = 0.32$) with larger effect sizes in the 100%IV condition. Also, after negative feedback it was larger in the 100%IV condition than the 80IV conditions ($F(1,34) = 5.3$, $p < .05$, $\eta_p^2 = 0.14$), while there was no such difference for positive feedback ($p = .27$).

To dissolve the interaction between Age Group, Task Complexity, and IV Valence, separate analyses were conducted for each age group. In young adults, we found that P3b amplitude in the low complexity condition was larger when positive IV was reduced than when negative IV was reduced ($F(1,16) = 9.3$, $p < .01$, $\eta_p^2 = 0.37$). Additionally, when negative IV was reduced P3b amplitude was larger in the high than low complexity condition ($F(1,16) = 15.4$, $p < .01$, $\eta_p^2 = 0.49$). None of these comparisons were significant for older adults (all *p*-values > .11; see Fig. 4).

2.2.3. P3b topography

An ANOVA with the factors Age Group (younger, older), Task Complexity (low, high), the planned contrasts on Anterior/Posterior (FCz vs. Cz, Cz vs. CPz, CPz vs. Pz), and the planned contrasts on IV reduction (100% IV vs. 80% IV) and IV Valence (80% PosIV vs. 80% NegIV) on the P3b valence effect (the difference of negative minus positive feedback) revealed a significant effect of CPz vs. Pz ($F(1,33) = 10.6$, $p < .01$, $\eta_p^2 = 0.24$) and interactions between Task Complexity and FCz vs. Cz ($F(1,33) = 7.3$, $p < .05$, $\eta_p^2 = 0.18$), Task Complexity and Cz vs. CPz ($F(1,33) = 12.1$, $p < .01$, $\eta_p^2 = 0.27$), IV Reduction and Cz vs. CPz ($F(1,33) = 9.5$, $p < .01$, $\eta_p^2 = 0.22$), Age Group, IV Reduction, and CPz vs. Pz ($F(1,33) = 15.8$, $p < .001$, $\eta_p^2 = 0.32$), and Age Group, Task Complexity, IV Valence, and FCz vs. Cz ($F(1,33) = 4.8$, $p < .05$, $\eta_p^2 = 0.13$).

To dissolve the interaction between Age Group, IV Reduction, and

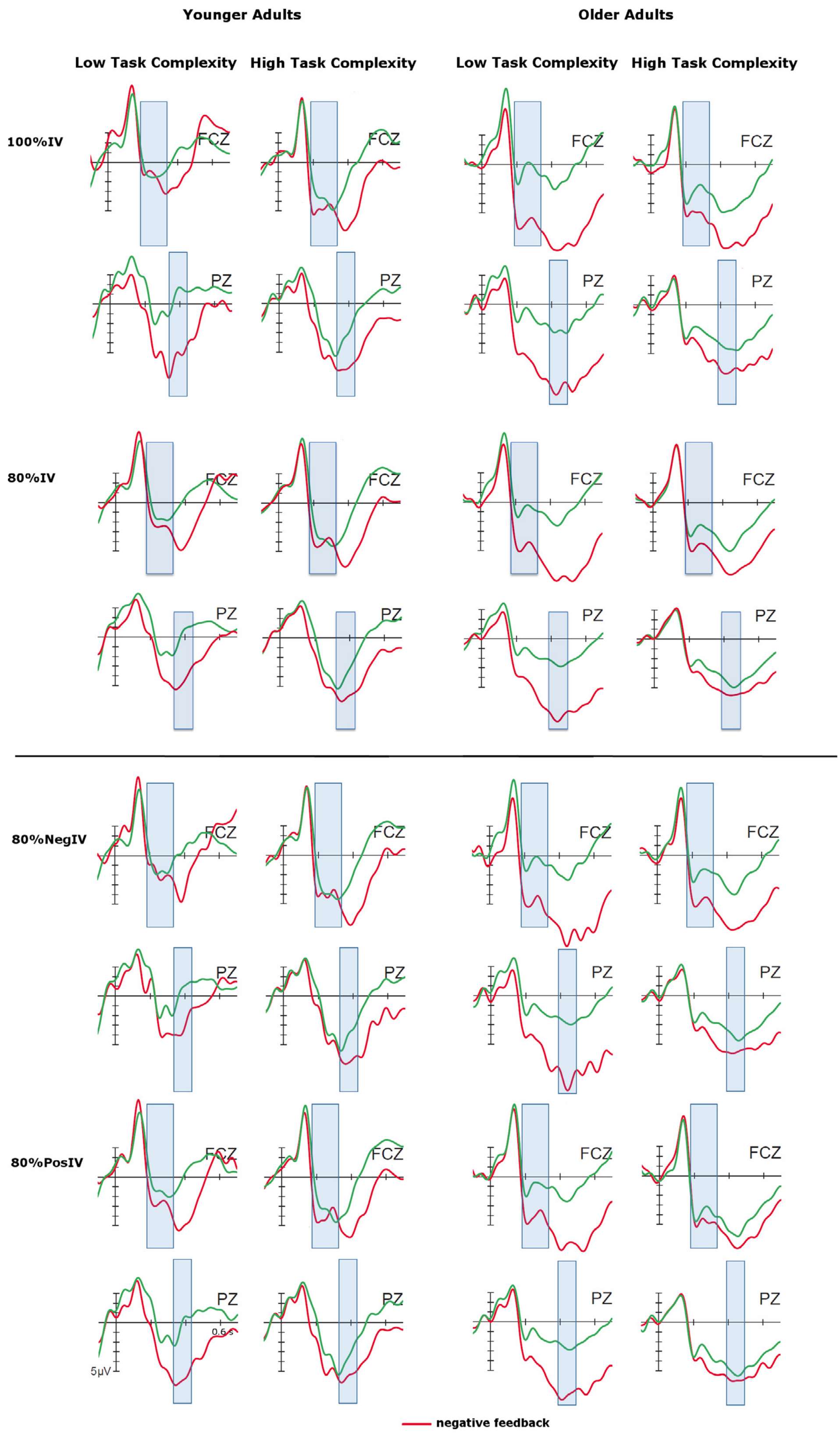

Fig. 4. Feedback-locked ERPs at electrodes FCz and Pz for younger and older adults in the low and high complexity conditions and for the different IV conditions, respectively. The upper part of the figure shows the 100%IV condition and the 80%IV conditions (averaged 80%NEgIV and 80%PosIV), the lower part shows the 80% NegIV and 80%PosIV condition.

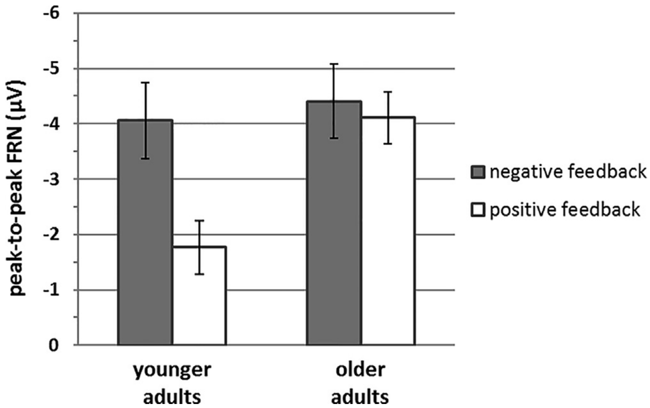

Fig. 5. Size of the peak-to-peak FRN for younger and older adults after negative and positive feedback measured at FCz.

Anterior/Posterior, separate ANOVAs with factors Age Group and Anterior/Posterior were calculated for 100%IV and the 80%IV conditions. These analyses revealed an interaction between Age Group and Anterior/Posterior (Cpz vs. Pz) in the 100%IV condition ($F(1,33) = 9.2$, $p < .01$, $\eta_p^2 = 0.22$), which was due to a more parietal topographical distribution of the P3b valence effect in younger (FCz < Cz: $F(1,16) = 5.7$, $p < .05$, $\eta_p^2 = 0.26$) than older participants (CPz > Pz: $F(1,17) = 36.9$, $p < .001$, $\eta_p^2 = 0.68$). In contrast, in the 80%IV conditions we found only a main effect for Anterior/Posterior (CPz > Pz: $F(1,33) = 6.9$, $p < .05$, $\eta_p^2 = 0.17$) demonstrating a fronto-central distribution of the P3b valence effect (see Fig. 6).

To dissolve the interaction between Age Group, Task Complexity, IV Valence, and Anterior/Posterior, separate ANOVAs with factors Age Group and Anterior/Posterior were calculated for task complexity and IV Valence condition. When IV was reduced in positive feedback, the P3b valence effect had a centro-parietal topography in the low complexity condition (FCz < Cz: $F(1,33) = 5.7$, $p < .05$, $\eta_p^2 = 0.15$), but a fronto-central distribution in the high complexity condition (Cz > CPz: $F(1,33) = 7.4$, $p < .05$, $\eta_p^2 = 0.18$). When IV was reduced in negative feedback, it showed a fronto-central distribution in the low complexity condition (CPz > Pz: $F(1,33) = 10.1$, $p < .01$, $\eta_p^2 = 0.24$) and the high complexity condition (CPz > Pz: $F(1,33) = 6.1$, $p < .05$, $\eta_p^2 = 0.16$; see Fig. 6).

3. Discussion

The aim of this study was to test the idea of an age-related positivity bias in feedback processing and learning against the possibility of a relevance focus that is dependent on the available processing resources. For this purpose, younger and older adults performed a probabilistic learning task in which they were to learn the correct response to a stimulus by means of feedback. The feedback's learning relevance was manipulated by varying the informational value of the positive and negative feedback stimuli, respectively. Additionally, to manipulate working memory demands, the task was conducted under two difficulty levels, and easy and a complex one. Behavioral as well as electrophysiological indices of feedback processing and learning were recorded.

In a memory test that was included after the learning phase, we found that younger participants remembered more stimulus-response assignments than older ones and all participants remembered more in the low complexity condition of the task (see Fig. 2). This memory test was mainly included as a means of a manipulation check. It shows that in general, the participants understood the instruction to search for two response keys in the high complexity condition (instead of merely sticking to the one they had found first), because for both younger and older participants the relative frequencies in the complex condition were higher than 0.50, the value that would be expected if only one correct key would have been reported. This is an important prerequisite for the interpretation of the present results because it demonstrates that the working memory manipulation actually worked.

In the accuracy data, we found increasing accuracies over the course of the experiment, i.e., learning, for both age groups. We found higher accuracies for younger than older adults. We also found an earlier and lower plateau in the high than low complexity task condition for both age groups demonstrating worse learning in the more difficult high

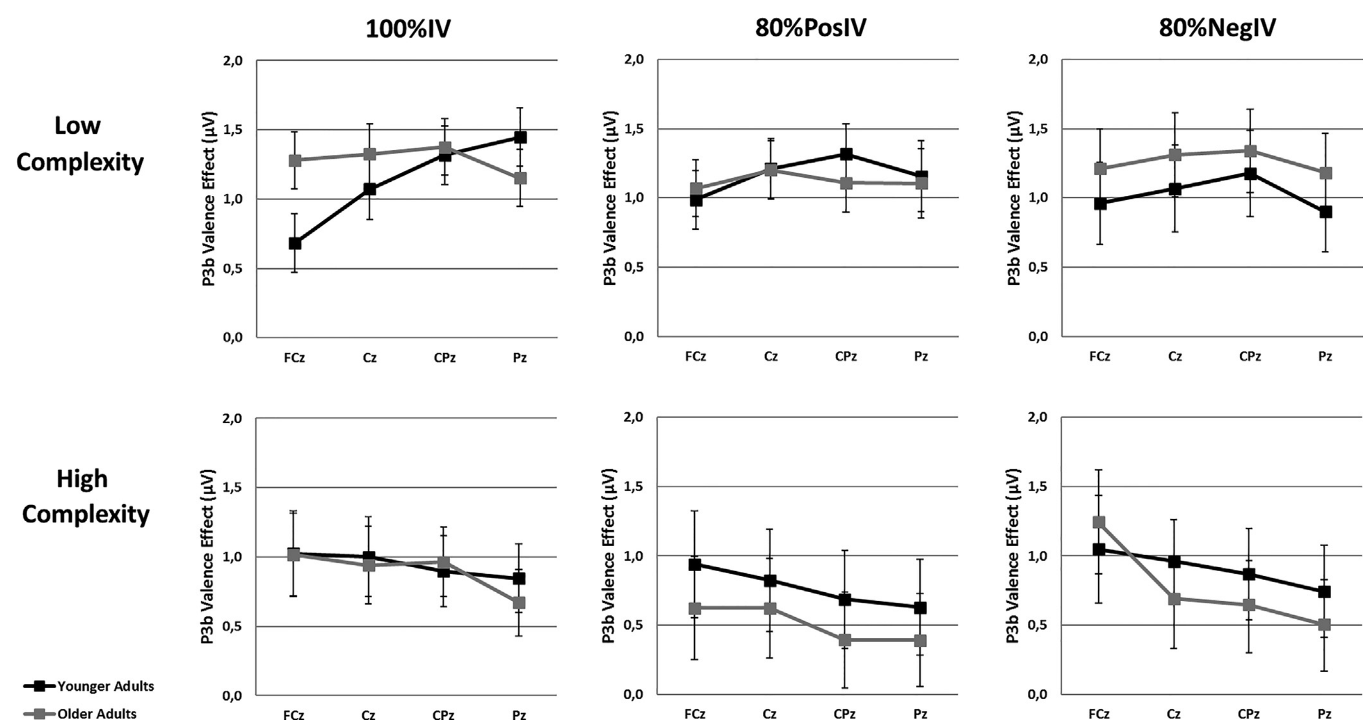

Fig. 6. Topographical distribution of the P3b valence effect (the difference of negative minus positive feedback) for the low and high task complexity and the 100% IV, 80%PosIV, and 80%NegIV conditions. Error bars denote the standard error of the mean.

complexity condition. Reaction times decreased over the course of the experiment, reflecting learning in both age groups. In the low complexity condition, reaction times for both age groups decreased already from the first to the second quarter. In the high complexity condition, this learning-related decrease occurred from the first to the second quarter for the young, but from the second to the third quarter in the older adults. Thus, older adults in the high complexity condition learned more slowly than in the low complexity condition and slower than younger adults. Additionally, in the low complexity condition older adults showed decreasing reaction times from the third to the fourth quarter in the 80%PosIV condition which was not found in the 80%NegIV condition. When looking at Fig. 3b, it becomes apparent that this is due to reaction times reaching an earlier and higher learning-related plateau in the 80%NegIV than in the 80%PosIV (and 100%IV) condition. Thus, reducing the information value of the negative feedback is detrimental for older adults and hinders learning, while such a reduction in positive feedback does not lead to impairments in learning. This speaks against the notion of an age-related positivity effect in feedback-induced learning. If older adults preferably used positive feedback for learning, one would expect that reducing the positive feedback's informational value would have detrimental effects. This result is in line with the idea put forward by Carstensen and DeLiema (2018), who argue that the positivity effect in older adults reflects a strategic change in motivation rather than neural or cognitive decline, i.e., older adults preferably process positive information if they have a choice, but they can process negative information as effectively if it is necessary for the task at hand.

When analyzing the ERP data, we found that the peak-to-peak FRN was larger for negative than positive feedback stimuli in young adults. This is the typical finding in learning paradigms in younger adults and can be explained by the fact that the more is learned, the less expected the negative and the more expected the positive feedback becomes (cf. Holroyd and Coles, 2002). In contrast, there was no such difference between positive and negative feedback in older adults, they displayed an FRN of the same size after positive and negative feedback. At first glance, this seems to indicate that older adults process positive feedback more strongly than younger adults and thus display a positivity effect during learning. However, as older adults also learned less and slower, this conclusion seems not justified. This result rather seems to indicate that a representation of the correct response builds up more slowly than in younger adults and therefore positive feedback elicits an expectancy violation longer (cf. Opitz et al., 2011) for older than younger adults. This means that during learning, older adults do not process positive feedback differently, they just have to rely on it longer than younger adults. Apart from this, no main effect of age was found in the peak-to-peak FRN, suggesting that the monitoring system is not as strongly affected by old age as has been suggested before and that it can, in principle, signal the detection of expectancy violations. This is in line with studies showing that the sensitivity to rewards and previously learned reward associations remains relatively intact in old age, whereas learning novel associations by reinforcements shows age-related impairments (e.g., Samanez-Larkin et al., 2014). Samanez-Larkin et al. (2012) showed that this could be due to age-related reductions in the structural connectivity between the dopamine system and prefrontal cortex. They speculated that this modifies the dynamic updating that needs to take place after a prediction error has been detected (for a review, see Ferdinand and Czernochowski, 2018). It is noteworthy that this result is probably also due to our adaptive trial procedure: When the task becomes less difficult due to timing limitations that are more appropriate for older adults, age difference in feedback processing become smaller (see also Eppinger et al., 2008). Finally, we did not find any interactions with task complexity or IV in the peak-to-peak FRN. Thus the basic monitoring process reflected in the FRN did not display a positivity bias nor a relevance focus and seems to process only the violation of expectancies. This is in line with a study by Li and colleagues (Li et al., 2018), who found that the FRN in young adults did only differentiate between positive and negative feedback in a learning task, while the following P3b was additionally influenced by how informative the feedback was.

Thus, in a next step, we examined the P3b as an index for a later, higher-order phase of feedback processing related to working memory updating after unexpected, task-relevant events. Here, we found that in general, the P3b was larger after negative than positive feedback. This is in line with an earlier study on feedback-induced learning using a similar learning task (Frank et al., 2005). This effect was found to be stronger in the low than the high complexity conditions of our task. Additionally, it was larger in the 100%IV condition than in the two 80% IV conditions of the task. This was mainly due to a reduction of the P3b after negative feedback. Together, these results demonstrate that a) during learning in this task, negative feedback seems to be perceived as more relevant and thus more updating is taking place after negative than positive feedback (cf. Polich, 2004, 2007) and b) the differentiation between positive and negative feedback is reduced in the more difficult task conditions, i.e., the highly complex one and the ones with less information available (80%IV conditions). Both effects are probably related to the fact that negative feedback is less expected when learning has taken place (in general, but even more so in the low complexity condition). This latter effect is in line with oddball studies demonstrating that the P3b is reduced in more difficult tasks (e.g., McCarthy and Donchin, 1981). Both effects were age-invariant. However, a third result for the P3b was found only for younger but not for older adults: Younger, but not older adults were sensitive to reductions in IV in the low complexity condition only. In this condition, average P3b amplitude was smaller and thus probably perceived task difficulty greater (e.g., McCarthy and Donchin, 1981), when negative IV was reduced than when positive IV was reduced. This means that updating was impaired when information value was reduced in negative feedback. This speaks in favor of a greater relevance of negative than positive feedback for learning in this task. In line with this interpretation, when looking at the ERPs in Fig. 4, this finding seems to be due to a smaller P3b after negative feedback in the 80%NegIV condition as compared to the 80%PosIV condition (although the respective interaction was not significant). In contrast, older adults seemed not to be sensible to reductions in IV, neither for positive nor negative feedback.

Replicating a typical age-effect, we found that the distribution of the P3b valence effect in the 100%IV condition had a clear parietal focus in young adults as compared to a fronto-central distribution in older adults. This is usually interpreted as a compensatory mechanism indicating that more frontal regions need to be recruited in older adults to evaluate the feedback and update working memory contents (Adrover-Roig and Barceló, 2010; Ferdinand and Kray, 2013; Ferdinand et al., 2016; Reuter-Lorenz and Lustig, 2005). In contrast, in the conditions with reduced IV, we found only a main effect for Anterior/Posterior demonstrating a fronto-central distribution of the P3b valence effect for younger and older participants. A possible explanation for this finding is that the IV reduction renders the task more difficult so that even younger adults need to invest more effort and to additionally recruit frontal brain areas to solve the task. This is also in line with the reduced differentiation between positive and negative feedback in P3b amplitude in both conditions with reduced IV. Another important finding regarding the P3b topography is linked to the IV valence effects: When IV was reduced in positive feedback, the P3b valence effect had a centro-parietal topography in the low complexity condition. However, it had a fronto-central distribution in the high complexity condition and in the conditions in which IV was reduced in negative feedback (low and high complexity conditions). Thus, the IV reduction in positive feedback seems to have little influence on the perceived task difficulty and does not need additional resource allocation or effort to learn. This again, speaks against the idea that positive feedback is preferably processed. On the contrary, it demonstrates the importance of negative feedback during learning for younger and older adults.

Why are the existing findings concerning a positivity bias in old age during feedback processing so mixed, while our results consistently point towards the greater importance of negative feedback during learning? A reason for this might be that we need to distinguish between different types of positivity biases. The first type relates to the basic ability to process positive and negative feedback and is strongly dependent on the neurobiological underpinnings of reward processing. Here, evidence is accumulating speaking in favor of an age-related positivity bias. For example, Samanez-Larkin et al. (2007) found that reward networks in older adults are less sensitive to loss cues than younger adults. Similarly, Cox et al. (2008) found a trend towards decreased brain responses to punishments in older adults. In contrast, processing of positive feedback and rewards seems to be relatively unimpaired (Rademacher et al., 2014; Samanez-Larkin et al., 2007; Spaniol et al., 2015). Because the FRN reflects a rather basic mechanism of feedback processing, also studies showing age-related impairments in the FRN can reflect this type of positivity bias, especially those showing less impairments in processing positive feedback at the same time (Eppinger et al., 2008; Pietschmann et al., 2011). However, not every age difference found in the FRN automatically reflects an age-related positivity bias because the FRN is also modulated by feedback expectancy, which can vary between younger and older adults (e.g., in learning tasks). Therefore, these studies have to be treated with caution (see also our reasoning concerning the FRN results in the present study). A second type of age-related positivity effect is more strategic in nature (cf. Carstensen and DeLiema, 2018), i.e., older adults might prefer to process positive information because their time horizon is restricted (cf. Mather and Carstensen, 2005), but they are not restricted to this focus. This type of positivity effect is related more strongly to task goals and task characteristics, e.g., whether or not preferably processing positive information is helpful, and thus results in this domain are rather mixed. For instance, in probabilistic learning tasks, like the one presented here, negative information carries more information with increasing learning and thus a focus on positive feedback is not very helpful for learning. In these cases, effects of feedback relevance might override preferences for positive feedback. In contrast, in probabilistic selection tasks that are designed to assess whether participants prefer to learn from positive or negative feedback, positive and negative feedback carry equal amounts of information. In this task, Frank and Kong (2008) found that older seniors showed more learning from negative compared with positive feedback (see also Hämmerer et al., 2010). Frank & Kong termed this a negative learning bias. However, it could also be interpreted as a strategic positivity effect, if it is assumed that older adults had the strategy to get rid of the less-preferred negative feedback as fast as possible. This interpretation is also in accordance with the definition of the positivity effect put forward by Carstensen and DeLiema (2018), who argue that the effect reflects age-related changes in motivation that direct behavioral strategies with the goal of receiving positive information which contributes to emotional well-being. Similarly, Di Rosa et al. (2017) found a positivity bias in older adults in the Iowa Gambling Task, where both learning from positive and negative feedback is important. An important factor that also needs to be taken into account and that can explain the mixed findings concerning the existence of a strategic positivity effect is the age of the older participants. The socio-emotional selectivity theory of aging proposes that older adults focus more on emotional well-being because they perceive time horizons as limited (Mather and Carstensen, 2005). In line with this, Frank and Kong (2008) found their learning bias only for older (mean age = 77 years), but not for younger seniors (mean age = 67 years) and Simon et al. (2010) did not a learning bias at all (older adults mean age = 70.3 years).

3.1. Limitations

In our P3b results, we found that only younger adults in the low complexity condition were sensitive to the reductions in information value. This raises the possibility, that the IV manipulation may have been too subtle to be processed in more demanding conditions and in older adults. That is, an exchange of informative feedback with uninformative feedback in 20% of cases might not have been enough to have an effect or alternatively, the tasks were not easy enough for these IV reductions to have an effect. However, the fact that reducing the IV of negative feedback led to detrimental effects in older adults learning performance (reaction times) speaks against this objection. Additionally, we think this is unlikely because our results consistently point against a positivity bias and towards a greater importance of negative than positive feedback during learning. However, although we tried to equal task difficulty via an adaptive deadline, we cannot exclude that a positivity bias in older adults could still be found in easier tasks or with a stronger IV manipulation.

Another limitation is related to the resulting sample size in the group of the younger adults. If a small to middle-sized effect size is assumed ($f = 0.15$) and an α of 0.05 together with a power of $\beta = 0.8$ is selected to examine the within-factors Task Complexity (low, high), Feedback Valence (positive, negative), and IV (100% IV, 80%PosIV, 80%NegIV) (as repeated measures with an assumed correlation among repeated measures of 0.75), a power analysis indicates a minimal group size of 18 participants per group. Thus, the slightly smaller sample size of the younger adults group ($n = 17$) could have affected the power of the results obtained.

3.2. Conclusion

Taken together, our results showed no hint of a positivity bias, i.e., a preferred processing of positive feedback by older adults. On the contrary, we found that older adults learned worse when the information value of the negative feedback was reduced, demonstrating that in this learning task negative feedback was more important for learning than positive feedback. Similarly, negative feedback seemed to be more important also for younger adults, because it modulated later higher-order feedback processing as indexed by the P3b. They showed reduced working memory updating and a more frontal P3b distribution indicating a higher processing effort in conditions in which the information value of negative feedback was reduced. Whether a positivity bias in old age could be found with easier learning tasks remains an open question for future research.

4. Materials and methods

4.1. Participants

Twenty-one younger (19 to 28 years) and 21 older adults (69 to 79 years) participated in this study. According to self-reports, all of them were in good health, had normal or corrected-to-normal vision, and were right-handed. Four younger and three older adults had to be excluded from the analyses because they did not have enough trials for EEG analysis in the negative feedback conditions. Thus, the final sample consisted of 17 younger (mean age = 22.8 years) and 18 older adults (mean age = 73.7 years; see Table 1 for a detailed description of the sample). The study was approved by the local ethics committee at Saarland University and conducted in accordance with the Declaration of Helsinki. All participants signed informed consent before the experiment and were paid 8 Euro per hour for their participation.

In order to assess their cognitive abilities, all participants performed the Digit-Symbol Substitution Test (DSST; adapted from Wechsler, 2008) as a marker of perceptual speed, the Counting Span (CS; adapted from Case et al., 1982) as a marker of working memory capacity, and the Multiple-Choice Knowledge Test (MWT-B; adapted from Lehrl, 1977) as an index of verbal knowledge. Younger adults were significantly better in the DSST ($t(33) = 5.29$; $p < .01$, two-tailed) and CS ($t(33) = 2.55$; $p < .05$, two-tailed) than older adults, while older adults performed better in the MWT-B ($t(33) = 3.86$; $p < .01$, two-tailed). This is consistent with the idea of preserved crystallized and

Table 1
Sample overview and results of psychometric tests (means and standard deviations; *p < .05, **p < .01, two-tailed).

	Age Group		*t*-Value
	Younger Adults	Older Adults	(*df* = 33)
Mean age (*SD*)	22.8 (2.8)	73.7 (3.2)	
n (female/male)	17 (8/9)	18 (8/10)	
MWT-B (correct items) (*SD*)	22.4 (4.9)	27.8 (3.4)	3.86**
DSST (correct items) (*SD*)	65.4 (12.3)	46.5 (8.6)	5.29**
CS (correct sequences) (*SD*)	5.5 (2.4)	3.7 (1.7)	2.55*

Note: MWT-B = Multiple Choice Knowledge Test, Version B (adapted from Lehrl, 1977); DSST = Digit Symbol Substitution Test (adapted from Wechsler, 2008); CS = Counting Span (adapted from Case et al., 1982).

Table 2
Response accuracies and response times for younger and older adults across the quarters of the probabilistic learning task. Standard error of the mean (SEM) in brackets.

Younger Adults						
	Low Complexity			High Complexity		
	100%IV	80% PosIV	80% NegIV	100%IV	80% PosIV	80% NegIV
Response Accuracy (SEM)						
Quarter 1	0.73 (0.04)	0.71 (0.04)	0.71 (0.03)	0.54 (0.03)	0.56 (0.02)	0.56 (0.03)
Quarter 2	0.86 (0.04)	0.86 (0.04)	0.85 (0.04)	0.63 (0.04)	0.65 (0.03)	0.65 (0.04)
Quarter 3	0.86 (0.04)	0.84 (0.03)	0.89 (0.04)	0.72 (0.04)	0.74 (0.04)	0.71 (0.04)
Quarter 4	0.90 (0.04)	0.89 (0.03)	0.90 (0.03)	0.72 (0.04)	0.74 (0.04)	0.73 (0.04)
Reaction Times in ms (SEM)						
Quarter 1	505 (28)	504 (29)	512 (30)	589 (34)	592 (37)	590 (40)
Quarter 2	480 (26)	482 (28)	476 (24)	555 (35)	564 (39)	569 (37)
Quarter 3	471 (25)	481 (22)	483 (21)	563 (34)	557 (33)	566 (33)
Quarter 4	492 (18)	498 (19)	488 (20)	561 (28)	553 (33)	560 (31)
Older Adults						
	Low Complexity			High Complexity		
	100%IV	80% PosIV	80% NegIV	100%IV	80% PosIV	80% NegIV
Response Accuracy (SEM)						
Quarter 1	0.52 (0.04)	0.54 (0.04)	0.56 (0.03)	0.50 (0.03)	0.51 (0.02)	0.57 (0.03)
Quarter 2	0.68 (0.04)	0.69 (0.03)	0.71 (0.04)	0.59 (0.04)	0.60 (0.03)	0.62 (0.04)
Quarter 3	0.77 (0.03)	0.77 (0.03)	0.76 (0.03)	0.66 (0.04)	0.66 (0.04)	0.70 (0.04)
Quarter 4	0.80 (0.04)	0.80 (0.03)	0.81 (0.03)	0.68 (0.04)	0.61 (0.04)	0.67 (0.04)
Reaction Times in ms (SEM)						
Quarter 1	672 (27)	679 (28)	676 (29)	655 (33)	669 (36)	656 (39)
Quarter 2	650 (25)	654 (27)	640 (23)	643 (34)	647 (38)	636 (36)
Quarter 3	657 (25)	647 (21)	635 (20)	608 (33)	611 (32)	622 (32)
Quarter 4	626 (18)	619 (19)	643 (20)	630 (27)	617 (32)	604 (30)

declining fluid intelligence with increasing age (see Baltes et al., 1999).

4.2. Task, stimuli and procedure

Subjects first filled in an informed consent, a demographic and self-reported health questionnaire, and a handedness rating (Oldfield, 1971). Afterwards, they were tested on the three psychometric tests described above before the main experiment started. The main experiment (programmed and presented using EPrime 2, Psychology Software Distribution) consisted of a probabilistic learning task in which participants had to learn the correct response to a stimulus via the feedback they received after their response. The stimulus material consisted of 24 colored images of objects (Rossion and Pourtois, 2004). Feedback was shown in form of a smiley. Each trial started with the presentation of a central fixation cross on a light grey screen for 500 ms, followed by an imperative stimulus. Within the 800 ms of stimulus presentation, subjects had to respond by pressing a response key. In case of a timeout, the message “Zu langsam!” (German for “too slow”) occurred on the screen. If subjects responded in time, they received a feedback (smiley) that was shown for 700 ms after a delay of 200 ms (blank screen; see Fig. 1a). To achieve a comparable difficulty level for younger and older participants, we applied an adaptive response deadline which adjusted the response time window to each individual (between a minimum of 800 ms and a maximum of 1500 ms) depending on the number of timeouts. The experiment started with a response deadline of 800 ms. Then, on each trial, the ratio between the total number of timeouts and the number of completed trials was computed and the time window was adjusted in steps of 100 ms for every 2% increase/decrease of timeouts.

To manipulate the feedback’s task relevance, we changed the information value (IV) of the feedback stimuli. In the 100% IV condition, feedback was informative in 100% of cases and thus positive and negative feedback should be equally relevant for learning. Participants got positive feedback in form of a laughing smiley in case of a correct answer and negative feedback in form of a sad smiley in case of a wrong answer. In the 80% IV conditions, we reduced the IV of the feedback by exchanging either the positive (80% PosIV condition) or the negative (80% NegIV condition) informative feedback by uninformative feedback which conveyed no information about whether the response had been correct or incorrect (a smiley without a mouth). In these conditions, the positive (in the 80% PosIV condition) or the negative (in the 80% NegIV condition) feedback should be less reliable and thus less relevant for learning, respectively (see Fig. 1b).

To manipulate working memory demands, all participants performed the task in a low and a high complexity condition (see Fig. 1a). In the low complexity condition, their task was to find one correct response out of two possible responses, i.e., after having seen the stimulus, they chose one of two response keys and received feedback about their choice. In the high complexity condition, their task was to find two correct responses out of four possible responses. Here, analogous to the low complexity condition, participants chose also one response key and received feedback about their choice. However, participants were encouraged to find out both correct response keys over the course of the experiment (see cover story and memory test below). The assignment between a stimulus object and the correct key(s) was counterbalanced across subjects.

We used a cover story to motivate our participants and to make sure that they tried to find both correct response keys in the complex condition. They were told to feed two/four colored dragons (indicated by the response keys). For this purpose, they had to find out which object(s) each dragon liked to eat by trial and error. Participants were instructed to answer as fast and as accurately as possible. They were told that it was important to find out both dragons that liked one object in the complex condition. Additionally, participants had to complete a short memory test at the end of each learning block, in which they were presented with the six objects again and had to choose the correct response key(s) that were associated with them during the learning block. Participants were informed about this memory test before the experiment started. To get familiar with the task, subjects completed a practice phase which they could repeat as often they wanted.

Every participant performed two blocks of the low complexity condition and two blocks of the high complexity condition in alternating order. The starting condition was counterbalanced across subjects. One block consisted of six different stimuli, which were presented 40 times each. Two of the six stimuli were assigned to the 100% IV condition, two stimuli were assigned to the 80% PosIV condition, in which the IV of the positive feedback was reduced, and two stimuli were assigned to the 80% NegIV condition, in which the IV of the negative feedback was reduced. Each block was divided into four parts, with a short break following each part.

4.3. EEG recording and pre-processing

Participants were comfortably seated in an electrically shielded chamber. While performing the probabilistic learning task, the electroencephalogram (EEG) was recorded using Brain Vision Recorder (Brain Products, Germany) from 59 Ag/AgCl active electrodes embedded in an elastic cap (extended international 10–20 system; Jasper, 1958) and amplified from DC to 100 Hz at a sampling rate of 500 Hz. The left mastoid served as a reference. The electrooculogram (EOG) was recorded from the outer ocular canthi and the right sub- and supraorbital ridges. Impedances were kept below 20kΩ. All EEG recordings were filtered offline by a digital band-pass filter from 0.1 Hz to 30 Hz and re-referenced to linked mastoids. Whenever the standard deviation in a moving 200 ms time interval exceeded 30 µV in ocular electrodes, data were marked as artifacts. EEG trials including eye movements were corrected using a linear regression approach (Gratton et al., 1983) and then averaged. Trials including other artifacts were excluded from averaging if the standard deviation in a 200 ms time interval was larger than 20 µV. A 100 ms prestimulus baseline was used for all ERP averages. Offline EEG processing was done using EEProbe (ANT).

4.4. Statistical analyses

As for behavioral data, we analyzed response accuracy (as relative frequencies) and reaction times. To assess learning, each learning block was divided into quarters. Timeout trials were excluded from all analyses. Additionally, the relative frequency of correctly remembered stimulus-response assignments in the memory tests at the end of each learning block were analyzed.

Analyses of EEG data were based on ERPs time-locked to feedback presentation. Time windows for ERP analyses were selected according to previous studies and on visual inspection of the waveforms. To separate the FRN from other ERP activity in the same time range, it was measured as the peak-to-peak difference between the positivity in a time window from 180 ms to 240 ms and the following negativity in a time window from 240 ms to 330 ms after feedback (cf. Holroyd et al., 2006; Ferdinand et al., 2012). Because the FRN is usually most pronounced at fronto-central sites (e.g., Miltner et al., 1997; Gehring and Willoughby, 2002; Holroyd and Coles, 2002), analyses were conducted at electrode FCz. The P3b was examined by means of mean amplitudes at electrode Pz where it is usually found to be largest (Polich, 2004, 2007). Because P3b latencies varied between age groups, it was measured between 330 ms and 430 ms for younger and 390 ms and 490 ms for older adults. To additionally examine the possibility of an age-related anterior shift in the P3b valence effect (difference of negative minus positive feedback), data were vector-normalized (McCarthy and Wood, 1985) and the topographical distribution was analyzed at FCz, Cz, CPz, and Pz.

Behavioral and ERP data were analyzed using repeated measures analyses of variance (ANOVAs) with an alpha level of 0.05. Greenhouse-Geisser correction for non-sphericity was applied when necessary. In this case, epsilon-corrected p-values are reported together with uncorrected degrees of freedom. To test our specific predictions on IV, an a-priori-defined orthogonal contrast was used instead of a three-level factor of IV: This contrast compared the 100%IV condition with the mean of the two 80%IV (i.e., 80%PosIV and 80%NegIV) conditions (IV Reduction contrast), the second compared the 80%PosIV and 80% NegIV condition (IV Valence contrast). Additional factors for the ANOVAs were Age Group (younger, older) and Task Complexity (low, high). For the behavioral analyses, the factor Quarter was included to examine our hypotheses concerning learning progress. To reduce the number of comparisons that were calculated to those necessary to test our hypotheses concerning learning progress, it was entered into the ANOVA as an a-priori-defined repeated contrast (quarter 1 vs. 2, 2 vs. 3, and 3 vs. 4). For analyses of the peak-to-peak FRN and the mean amplitude P3b, the factor Feedback Valence (positive, negative) was included. For topographical analyses, the factor Anterior/Posterior was included. To reduce the number of comparisons, it was entered into the ANOVA as a repeated contrast (FCz vs. Cz, Cz vs. CPz, CPz vs. Pz). In case of post-hoc comparisons, the Bonferroni correction was applied and corrected p-values are reported.

Due to the following theoretical and methodological reasons, for ERP data direct age group comparisons and correlation analysis over both age groups have not been conducted in this study: a) Differences in ERPs between age groups can have multiple sources which can be structural (skull thickness, cortical thickness, …) or functional (cognitive decline, effort, strategies …) in nature. If we found significant effects including age, we would not be able to determine whether these effects were due to structural or functional reasons, although the functional ones are those of interest when using EEG. b) For this reason, we formulated our hypotheses in a way that they reflect our predictions about specific condition-related patterns within each age group, i.e., we predict different patterns of results in each age group which reflect processing in case of a positivity effect or a relevance effect (which both rather reflect a change in processing strategy as a consequence of cognitive decline). c) Also for statistical reasons, we decided to not dissolve interactions which we had no specific hypotheses for to reduce multiple comparisons.

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