Enhanced self-esteem reactivity in response to social prediction errors in adolescence.

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Abstract

Self-esteem is an important cornerstone of mental health across the lifespan. Throughout life, but perhaps particularly during the socially sensitive phase of adolescence, self-esteem is shaped by appraisals from other people. Previous work in adults showed that momentary fluctuations in self-esteem are best explained not only by whether we are liked by others but whether we are liked more or less than we expected ('social prediction errors'). However, it is unclear if adolescents and adults differ in this regard. To address this gap, this study examined age-related differences in how social experiences shape self-esteem in 141 participants aged 10 to 40 years. We combined data from an experiment that simulated peer evaluation in a social media context with daily-life measures of self-esteem and social interactions collected using ecological momentary assessment. Self-esteem reactivity in response to social experiences varied with age: in the experiment, self-esteem reactivity in response to unexpected social feedback increased during adolescence and decreased again during adulthood. In daily life, self-esteem reactivity decreased with age in response to the pleasantness of a previous social interaction, but also in response to naturalistic social prediction errors (the difference between expected and perceived pleasantness of a social interaction). Self-esteem reactivity in the lab was moderated by daily-life self-esteem reactivity, demonstrating a convergence between lab observations and everyday experiences. Our findings suggest that adolescents' self-image is highly malleable during adolescence, a socially dynamic phase of life, where a key developmental challenge is the reconfiguration of self-image within new social environments.

Significance Statement

Across species, adolescence is a time of heightened sensitivity to social rewards and punishments. As self-acceptance and social acceptance are tightly interwoven, the effect of social acceptance on self-esteem might be emphasized during this period. Using data from laboratory and naturalistic settings, we found that self-esteem is shaped by social experiences and that this effect changes across adolescence and adulthood. In particular, self-esteem reactivity to unexpected social feedback peaks in late adolescence/young adulthood. Our findings, which are consistent across experimental and smartphone-based naturalistic measures, suggest that increased self-esteem reactivity to social feedback might allow adolescents to quickly adapt to a quickly changing social environment and in turn contribute to developing a sense of self.

Main Text

Introduction

You have just had a nice chat with your neighbor, who usually only grumbles - does that make you feel better about yourself? There is a good chance that it does: research has shown that both processes – how I perceive myself and how I perceive my interactions with others – influence each other and that self-acceptance and social acceptance are inextricably interwoven, both in the moment and across longer time spans (1-3). For adolescents, who are increasingly exposed to social feedback via social media, the effect of social experiences (e.g. being liked by others online) on self-esteem might be particularly emphasized (4, 5). In this study, we asked the question of whether in a controlled lab environment, and in daily-life, self-esteem reactivity towards (un)expected social feedback is different in adolescents as compared to adults.

Previous studies have indicated that adolescents exhibit heightened fluctuations in their self-esteem, characterized by more pronounced increases and declines on a day-to-day basis (6, 7). It is conceivable (but untested) that social experiences play a particularly important role in shaping such self-esteem dynamics during adolescence. Evidence suggests that adolescence, across species, is a socially particularly sensitive phase in life ((8, 9) for review): adolescents exhibit heightened emotional and neural responses to social evaluation (8, 10, 11) and heightened susceptibility to peer influence (12-15). Besides, there is some correlational evidence from observational studies showing that social experiences like peer attachment and positive parenting, are negatively associated with overall self-esteem variability (16-18). Moreover, previous experimental work presented results showing that young adolescents tend to internalize peer rejection (i.e. peer rejection affects their self-view), whereas young adults rather externalize it and show self-protective biases (19). Yet, how exactly social experiences shape adolescent self-esteem dynamics on short-term scales remains unknown.

This gap in knowledge is lamentable given the great (developmental) significance of self-esteem: On average, self-esteem has been shown to be lower during adolescence than in adulthood or childhood (7, 20, 21). Further, low self-esteem in adolescence is predictive of future risks that persist into adulthood, including mental and physical health problems, substance dependence, criminal behavior, limited economic opportunities, and reduced life and relationship satisfaction (22-24). Also in adult age, self-esteem is linked to mental health (25-27), academic achievement (28-30), and satisfaction with social relationships (1, 2).

To close this gap, in this study, we build on recent computational work that provided novel insights into the dynamics that underly socially triggered fluctuations in self-esteem (31, 32). This line of research uses ideas from Reinforcement Learning to demonstrate that self-esteem changes depend on both the valence of social feedback (e.g., whether you are liked or not) and expectations about feedback (e.g., whether you anticipated that this person would like you or not). In line with this account, self-esteem in young adults was shown to be shaped by social feedback that was more positive or more negative than expected ("social prediction errors" (31, 32)). Humans use such social prediction errors to update expectations about how much other people liked them, and to simultaneously update their subjective feelings of self-worth. On a neural level, social prediction errors were encoded in ventral striatum as well as in subgenual anterior cingulate cortex, and momentary updates in self-esteem in response to prediction errors were tracked by ventromedial prefrontal cortex. Here, we applied this account to investigate how social experiences shape short-term fluctuations in self-esteem from late childhood to mid-adulthood. We were specifically interested in whether self-esteem reactivity towards social prediction errors is pronounced during adolescence.

Social prediction errors serve as a key learning signal for learning about the value of stimuli, and actions, but also self-worth from others (31, 33). This process is crucial for adolescents as they adapt to new social environments and shape their self-image. Thus, beyond the question of self-esteem reactivity towards social prediction errors, we examined age-related changes in self-image and expectations of being liked. We examined self-esteem reactivity to social prediction errors, age-related changes in self-image, and expectations of being liked by others. Consistent with (19), we anticipated a more positive self-image and higher expectations of being liked with increasing age, akin to a self-protective bias that was previously found to be stronger in adults than in adolescents (19).

To investigate this question, we conducted two studies to explore the relationship between expectations of being liked, prediction errors, and self-esteem. In study 1, we employed an online experimental paradigm with participants spanning three decades of the lifespan (10-40 years old). During the experiment, we simulated social media feedback to examine the effects of being liked vs. disliked and social prediction errors (i.e., combined influence of expectations about being liked and valence of feedback) on self-esteem. Study 2 utilized smartphone-based EMA over eight days to collect daily-life self-esteem and social experience ratings from the same participants that took part in study 1. This approach allowed us to explore the naturalistic interplay between social experiences and self-esteem dynamics and to relate them to the data gained in the lab. Additionally, using EMA data, we approximated naturalistic social prediction errors, i.e., whether a social interaction in daily life was more or less pleasant than expected (mirroring experimentally induced social prediction errors in the lab). We hypothesized that the influence of social experiences on self-esteem is more pronounced in adolescence compared to adults and that this is explained by higher self-esteem reactivity to social prediction errors, both in the controlled lab environment and in daily life.

Results

Study 1 Social Evaluation Task.

We were interested in whether there were age differences in reactivity in response to social feedback which may contribute to changes in self-esteem. To experimentally test this, we used a realistic task (31, 32) simulating a social media context, designed to capture two aspects of social feedback (i.e., feedback valence and social prediction errors). The experimental task was embedded in a cover story in which participants were asked to create an online profile akin to a social media profile (including a photo and personal questions about themselves) (Figure 1A). They believed that they would receive social feedback on this profile. To generate social prediction errors, expectations towards raters were experimentally manipulated: raters (supposedly other participants, according to the cover story) were assigned to one of four groups, depending on how often they liked profiles from others, i.e. how likely it was to receive a like from each rater group (Figure 1B). The rater groups and thus also the probability of receiving a like were signaled using color cues. Before the experiment started, participants learned about the rank ordering of the rater groups in terms of the rater's benevolence (denoted by color pairs) and could only enter the experiment when they met the learning criterion of 6x6 subsequent correct answers. Consequently, these color cues formed reliable expectations in our participants about how likely they were to receive a like from the single raters (i.e., high expectations of receiving a like from the most benevolent group and low expectations from the most unfriendly group). During the main experiment, in each trial, participants first saw the name and color cue of a rater and predicted whether they expected to get a like or a dislike from them (Figure 1B). Subsequently, feedback (i.e., likes or dislikes given by peer raters) was presented. After every 2-4 of such feedback trials, participants rated their self-esteem. Throughout the experiment, each rater was presented once. The 192 raters were randomized across trials.

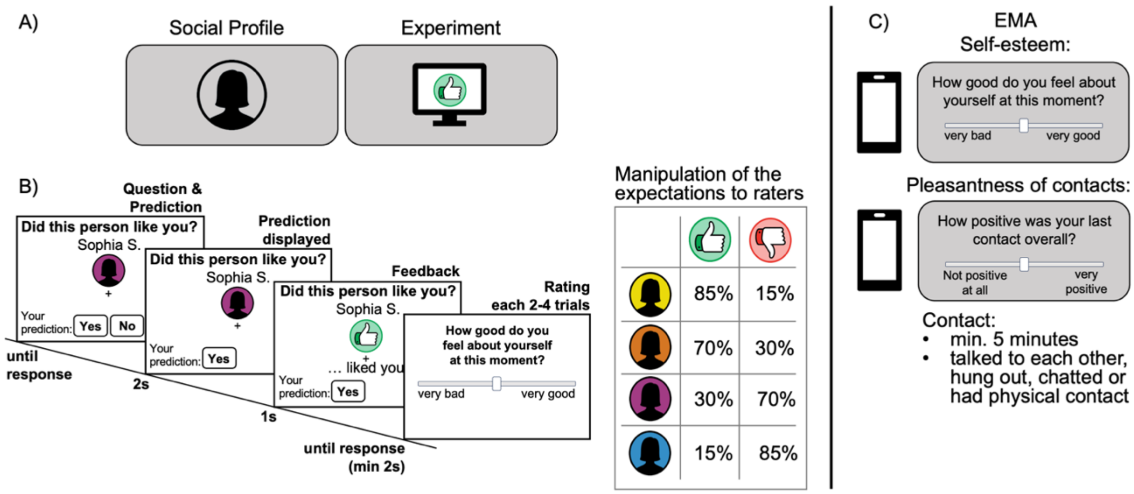

Figure 1. Experimental design A) As part of a cover story, participants were asked to create an online personality profile akin to a social media profile. They were told that this profile would be rated by other participants ('raters'). A few days later, participants conducted the online experiment. B) During the experiment, participants were presented with a rater name and a color cue indicating overall rates of giving likes toward other participants. Participants were instructed to predict whether a rater would like or dislike their profile (taking the color of the rater group into account). Participants rated their current level of self-esteem every 2-4 trials. Importantly, raters were divided into four color groups (right panel), randomized across participants, representing different levels of benevolence, i.e., higher or lower probabilities of liking other profiles. Participants learnt the rank order of the probabilities of receiving a like before entering the experiment. C) To gather data on participants' self-esteem and social experiences in a daily-life context, participants were required to complete an Ecological Momentary Assessment (EMA) for eight (predominantly) consecutive days. This assessment involved answering a series of questions multiple times per day, with some questions repeated 10-times (e.g., self-esteem) and others repeated 4-times a day (e.g., pleasantness of social interaction).

Expectations about being liked.

First, we investigated participants' expectations about being liked by the other raters, and whether this showed age-related differences using mixed logistic regression models. We found that rater groups significantly influenced the predictions (FE=2.006, SE=0.141, p-value<0.001, see Table 1 and Figure S2). That is, participants predicted that their profile would be liked more often by raters who were benevolent towards other profiles. We observed a main effect of age on the expectation about being liked (FE=0.206, SE=0.101, p-value=0.041): younger participants predicted to be liked slightly less than older participants, independent of the rater group. Interestingly, younger participants were closer to the true probability of being liked (50% across all conditions, as defined by our experiment), whilst older participants over-estimated the probability (akin to a "positivity bias") ($\text{mean}_{<18}$=49.69%, $\text{mean}_{\geq 18}$=55.98%). We found that this age effect was moderated by trial number (FE=-0.042, SE=0.020, p-value=0.032; trial number considered as repetitions within rater groups). As Figure 2A indicates, the age differences in the expectations about being liked got smaller as the experiment progressed. That is, older participants were able to adjust their initial positivity bias by converging towards predicting the true probabilities later in the experiment. This interpretation is backed up by an observation that 56.36% of participants <18 predicted a like in trial 1 whereas it was 69.51% for participants ≥18. Exploratively, we tested whether age effects were influenced by the benevolence of the rater groups (allowing 3-way interactions: $\text{probability}_{\text{like}}$ x $\text{age}_{\text{linear/quadratic}}$ x trial number). We found that the higher convergence towards true probabilities with increasing age was specific for the less benevolent rater groups (probability$_{like}$ x age$_{linear}$ x trial number; p=0.026; Supplementary Results 1 & Table S1), likely due to older participants initially overestimating being liked by these groups (Figure S2).

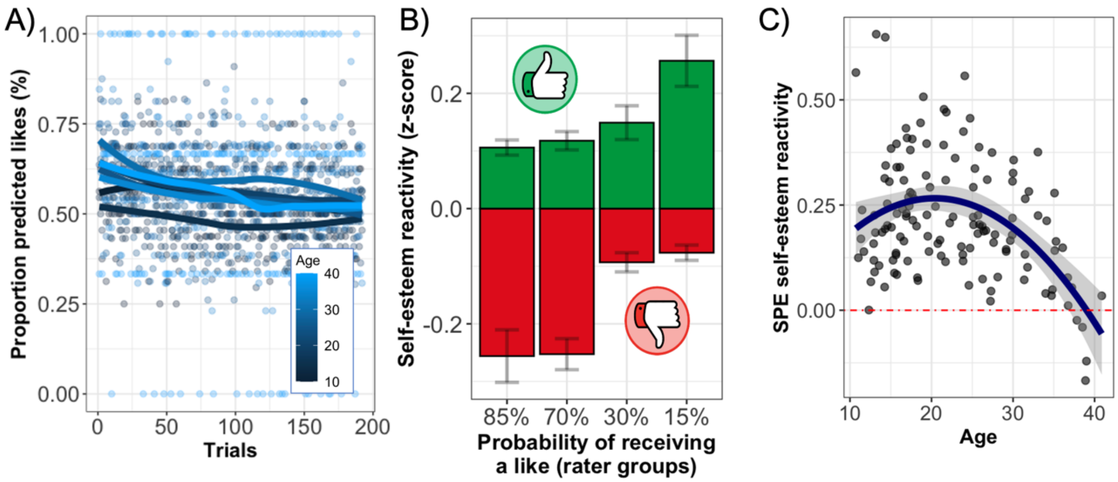

Figure 2. Results from the experimental social evaluation task. A) Expectation about being liked, i.e., proportion of predicted likes (%) across rater groups. We found age differences in the proportion of predicted likes which became less pronounced over the course of the experiment. For visualisation purposes, we plot six age groups, whilst age was included in the model as a continuous regressor in the analyses reported here. The dark blue dots/line represent the mean proportion rates from the participants aged 10-14. Increasingly light color represents the older age groups for those the slope gets steeper. B) Self-esteem changes plotted as standard deviations from the individual mean (y-axis; only for visualization purposes) per rater group (i.e., probability of receiving a like, x-axis). Bars represent the averaged individual means. Green bars are reactions towards likes, red bars towards dislikes. Grey error bars reflect standard errors of the individual means. Z-scores are for visualization purposes only, mixed models and reported results include the actual score. C) Age differences in self-esteem reactivity towards social prediction errors. x-axis: age; y-axis: SPE self-esteem reactivity. SPE self-esteem reactivity was based on a mixed model, fitting self-esteem dynamics by an interaction of probability$_{Like}$ x valence. For visualization purposes, the y-axis represents the correlation between SPE condition and the predicted changes in self-esteem. The correlation is positive on average as SPE self-esteem reactivity increases with increasing SPEs. Each point represents the individual extracted correlation.

Table 1. Results of the mixed logistic regression on expectations about being liked

Predictor	*FE*	*SE*	*p-value*
Intercept	**0.456**	**0.128**	**<0.001**
Probability$_{Like}$ (rater groups)	**2.006**	**0.141**	**<0.001**
Trial number (within rater groups)	**-0.185**	**0.025**	**<0.001**
Age linear	**0.206**	**0.101**	**0.041**
Age quadratic	-0.177	0.096	0.065
Trait self-esteem (Rosenberg)	**0.393**	**0.090**	**<0.001**
Age linear x Trial number	**-0.042**	**0.020**	**0.032**
Age quadratic x Trial number	0.018	0.019	0.349

Self-esteem dynamics as a function of social prediction errors.

In a next step, we were interested in whether changes in self-esteem during the experiment can be related to feedback valence (like vs. dislike) and social prediction errors (SPE), and whether age moderates these associations. We replicated previous findings from adult samples (31, 32) showing that receiving likes had a positive impact on self-esteem, while receiving dislikes had a negative impact ('valence reactivity', see Figure 2B, F=65.88, df=321.00, p-value<0.001). This effect was not significantly moderated by age (linear: F=1.57, df=321.98, p-value=0.210; quadratic: F=3.53, df=321.18, p-value=0.061). We then investigated the influence of social prediction errors (SPE), defined as unexpected likes or dislikes (which was experimentally manipulated by the benevolence of the 4 rater groups and their approval rates) on self-esteem. Since prediction error increased for likes as the probability of receiving likes decreased, while it decreased for dislikes, self-esteem reactivity to SPE was reflected in a $\text{probability}_{\text{Like}}$ x valence interaction. This interaction was significant ('SPE reactivity', F=52.31, df=20617.77, p-value=<.001), replicating previous results in an adult sample (31, 32). That is, self-esteem changes were larger, when SPEs were high (i.e., unexpected feedback), and smaller when SPEs were low (see Figure 2B). Intriguingly, this effect was significantly moderated by quadratic age (interaction effect of age^2 x $\text{probability}_{\text{Like}}$ x valence). As Figure 2C shows, the effect of SPEs on self-esteem increased during adolescence, and decreased subsequently during adulthood (age quadratic: F=4.85, df=20617.28, p-value=0.028; age linear: F=2.93, df=20618.97, p-value=$0.087^{\text{n.s.}}$). This indicates that after SPE reactivity reached a peak in late adolescence / emerging adulthood, SPE reactivity decreased again from young adulthood to mid-life. This might point to a more stable sense of self as individuals grow older, where self-esteem becomes less dependent on what other people think of them. For further analyses regarding the effect of the correctness of participants' predictions and the effect of participants' and raters' gender see Supplementary Results 4 and Table S4. For an explorative analysis on the reverse effect of self-esteem on predictions to be liked, see Supplementary Results 5 and Figure S4.

Study 2. Self-esteem, pleasantness of social interaction and their association in everyday life (EMA).

In the data gathered during our controlled online experiment, we found evidence that self-esteem is influenced by the valence of social feedback as well as social prediction errors. Critically, we found that age modulates the effect of social prediction errors on self-esteem. In a next step, we sought to explore whether these associations can also be observed in participants' daily life. To this end, we used EMA data collected in the same participants via their smartphones (see Figure 1C).

On a scale ranging from 0 to 100, participants indicated their momentary self-esteem (averaged daily mean =66.76, averaged daily variability =11.03, rated 10x/day, see Figure S3) as well as pleasantness of the last social interaction (i.e., social pleasantness; averaged daily mean = 72.29, averaged daily variability= 12.29, rated 4x/day, see Figure S3). For details on mean levels / variability in self-esteem and social pleasantness ratings as well as for age effects therein see Supplementary Results 6.

Previous literature demonstrated a reciprocal relationship between self-esteem and social experiences over longer time scales, i.e. period of a year (1, 2). Our analysis of EMA data extended these findings by revealing a significant relationship between social pleasantness at timepoint t and the previous rating of self-esteem_{t-1} (i.e., the rating that was given at the prompt before, median=4.50 hours of time lag, FE=4.101, SE=0.404, p-value<0.001). That is, the higher self-esteem at the prompt before the rated social interaction, the more pleasant this subsequent interaction was experienced (see Figure 3A).

At the same time, mirroring a pattern observed in our experimental setting in study 1, we show that social $\text{pleasantness}_{t-1}$ affected subsequent self-esteem_t (FE=0.894, SE=0.349, p-value=0.011). This indicates that the more pleasant a social interaction was rated in the previous prompt, the higher was the current self-esteem (see Figure 3B). In sum, we found bidirectional interaction in the time-lagged analyses between social pleasantness and self-esteem. For a set of control analyses with respect to timing of the EMA prompts, see Supplementary Results 7.

Age moderates the effect of social pleasantness on self-esteem in everyday life.

We were particularly interested in whether age moderates the bidirectional association of self-esteem and social interaction as observed in the EMA data. Notably, we found substantial differences between the two directions of the effect (self-esteem → social pleasantness vs. social pleasantness → self-esteem). The effect of previous self-esteem$_{t-1}$ on social pleasantness$_t$ was not significantly moderated by age (FE=0.042, SE=0.391, p-value=0.914). In contrast, age significantly moderated the influence of previous social pleasantness$_{t-1}$ on self-esteem$_t$ (FE=-0.743, SE= 0.308, p-value= 0.016) Figure 3 shows that the influence of previous social pleasantness on self-esteem decreased with increasing age (Figure 3, D&E). Both models were not significantly improved by adding age as a quadratic term, i.e., we found no evidence for a quadratic age effect (model comparison: p-value$_{SE \rightarrow social\ pleasantness}$ = 0.503, p-value$_{social\ pleasantness \rightarrow SE}$ = 0.295). Taken together, these results show that the influence of daily-life social experiences on self-esteem changes from late childhood to mid-adulthood.

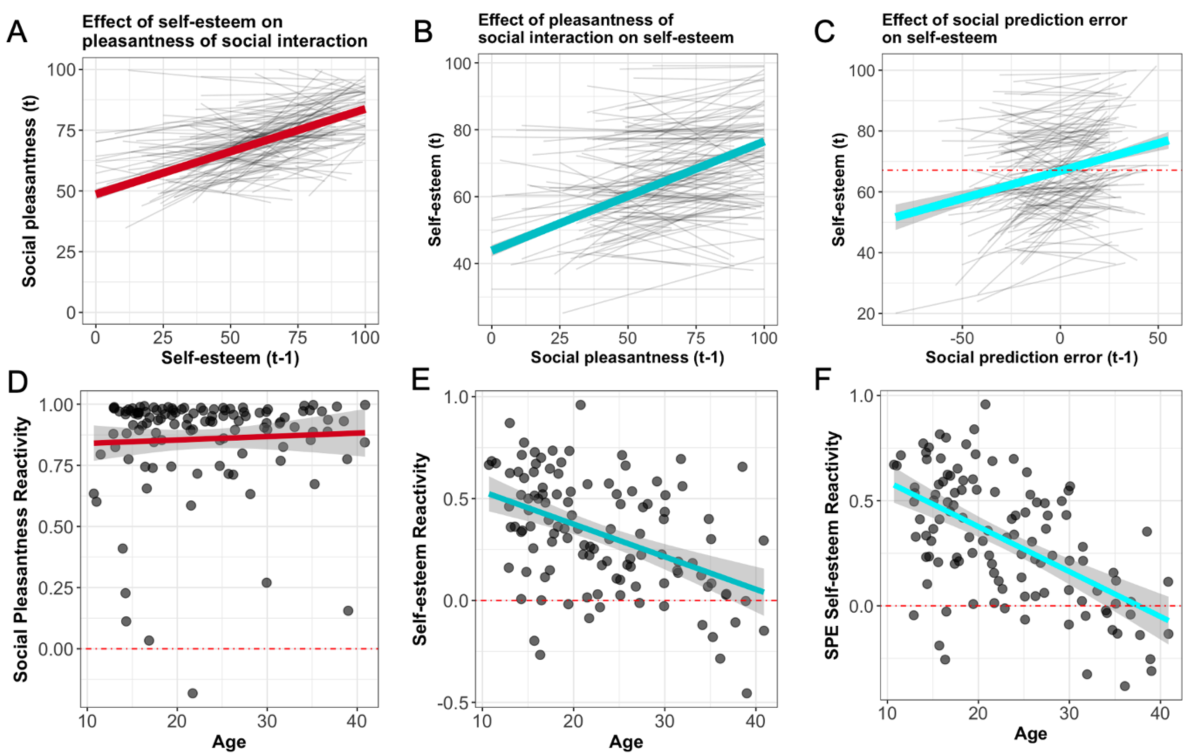

Figure 3. Association of self-esteem and pleasantness of social interactions in everyday life (EMA). A) Effect of self-esteem on the subsequent rating of pleasantness of the last social interaction ('social pleasantness') across the whole sample B) Effect of social pleasantness on the subsequent self-esteem rating across the whole sample C) Effect of social prediction errors on the subsequent self-esteem rating across the whole sample. The red dashed line stands for population mean, i.e., self-esteem exceeds the average for positive SPEs and undercut it for negative SPEs D) Social pleasantness reactivity. Self-esteem influence on social pleasantness did not change significantly with age. We plot individual correlations between fitted values of social pleasantness$_t$ (mixed model) and raw ratings of self-esteem$_{t-1}$ as a function of age. High correlations indicate that the previous rating of social pleasantness$_{t-1}$ and self-esteem$_t$ are strongly linked to each other. Shades indicate standard error of the regression line (R-package ggplot2) E) Self-esteem reactivity. The

influence of social pleasantness on subsequent self-esteem ratings decreased with age (y-axis: correlation between social pleasantness$_{t-1}$ and fitted self-esteem$_{t}$; x-axis: age; shades: standard error of the regression line). F) SPE self-esteem reactivity. The influence of social prediction error on subsequent self-esteem ratings decreased with age (y-axis: correlation between SPE$_{t-1}$ and fitted self-esteem$_{t}$; x-axis: age; shades: standard error of the regression line).

Momentary self-esteem is modulated by daily-life social prediction errors which undergoes age-related differences.

Formal models describing an association of social experience and self-esteem propose that not only the valence of social experience (i.e., in our EMA data, the pleasantness of social interactions), but also social prediction errors, (i.e., whether the pleasantness deviated from participants' expectations), influence self-esteem (32). We sought to test this hypothesis in our EMA data.

To implement this approach, based on the idea of building expectations about the pleasantness of social interactions from past experiences, we aimed to approximate daily-life social prediction errors by quantifying whether a social interaction was more or less pleasant than anticipated. We followed a methodology to approximate daily-life PEs introduced by (34) (see Methods for more details): the daily-life social prediction error (SPE) for an individual on a given prompt was calculated as the difference between the expected social pleasantness and the actual rating of social pleasantness. We defined expectation as a moving average based on previous ratings and updated prompt-by-prompt by the PE which was weighted by a fixed learning rate. Thus, this signed prediction error does not merely represent whether an interaction was pleasant or unpleasant (valence effect) but whether it was higher or lower than subjectively expected (SPE effect).

Similarly to the pattern observed in the lab experiment in study 1, we found that the prediction error of social pleasantness at t-1 predicted self-esteem at t (FE=0.827, SE=0.289, p-value=0.004, Figure 3C). This daily-life social prediction error reactivity decreased with age (age x SPE$_{t-1}$ interaction, FE=-0.663, SE=0.255, p-value=0.009, Figure 3F). That is, the less expected a previous positive social interaction was, the stronger was the subsequent positive effect on self-esteem and this association became weaker with increasing age. As a control analysis, we calculated a model including both, previous raw ratings on self-esteem$_{t-1}$ and social pleasantness$_{t-1}$, as well as the prediction errors of both (deviation from the expected rating at t-1). we observed that only previous social prediction errors, not the raw rating of social pleasantness significantly predicted the upcoming self-esteem (FE=1.093, SE=0.520, p-value=0.036, see Supplementary Results 8). Taken together, these results show that parallel to the dynamics observed in social evaluation task, social prediction errors affect subsequent self-esteem in daily life and that this self-esteem reactivity is subject to age-related differences. Particularly, self-esteem reactivity is strongest in adolescence and decreases with increasing age. Interestingly, the age effect was specific for the social modulation of self-esteem (i.e. effect direction$_{\text{social pleasantness}\rightarrow\text{SE}}$) and not significant for the effect of unexpectedly high or low self-esteem on social pleasantness (i.e., effect direction$_{\text{SE}\rightarrow\text{ social pleasantness}}$, namely the interaction effect age x self-esteem prediction error at t-1: FE=0.236, SE=0.303, p-value=0.436). Similarly to the time-lagged analyses using raw ratings reported above, models for both directions, (ie., direction$_{\text{SE}\rightarrow\text{social pleasantness}}$ and direction$_{\text{social pleasantness}\rightarrow\text{SE}}$) did not improve by including a quadratic age term.

Study 1 and 2. Association between self-esteem dynamics in the lab and in daily life.

Next, we investigated whether the self-esteem reactivity assessed in the lab (study 1) was moderated by self-esteem reactivity in daily life, i.e. whether daily-life social self-esteem reactivity was related to the self-esteem reactivity to social prediction errors measured in the online experiment. To test this, we extracted the individual estimates of the effect of social pleasantness$_{t-1}$ on self-esteem$_{t}$ from our EMA data (via a random slope). In the same way, we derived the estimates of influence of social prediction error$_{t-1}$ on self-esteem. In two separate mixed models we examined whether these EMA estimates of social self-esteem reactivity moderated self-esteem reactivity to social prediction errors in the social evaluation task (i.e., 3-way interaction effect of probability$_{Like}$ x valence x EMA self-esteem reactivity), while controlling for age. Strikingly, we found that the degree of SPE reactivity in the experiment, was moderated by self-esteem reactivity in daily life (FE=7.023, SE=0.304, p-value=0.021). As Figure 4 shows, those showing higher SPE reactivity in the experiment were also those whose self-esteem in daily life was more strongly influenced by social pleasantness per se, (see Figure 4A; FE=7.023, SE=0.304, p-value=0.021), but also by daily-life social prediction errors (see Figure 4B, FE=-1.119, SE=0.522, p-value=.032), demonstrating a correspondence of self-esteem reactivity in the lab and in daily life. That is, the computational dynamics shaping self-esteem based on social prediction errors explain variance in self-esteem changes in daily life.

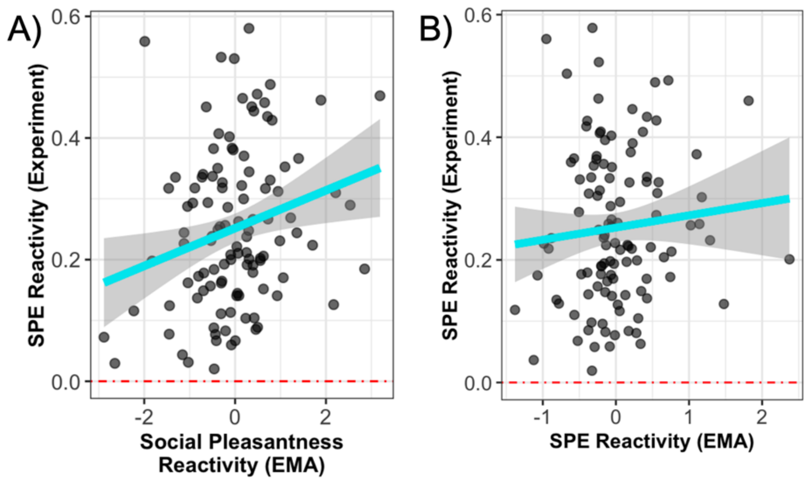

Figure 4: Associations of self-esteem dynamics measured in the experiment and in daily-life (EMA) A) Association of self-esteem reactivity towards social pleasantness (daily-life) and self-esteem reactivity towards social prediction errors (experiment). To get EMA estimates, we extracted participant-specific random slopes for the effect of social pleasantness at t-1 on self-esteem for each individual. These estimates moderated SPE reactivity in the experiment, indicating that those who showed higher SPE reactivity in daily-life also showed pronounced SPE reactivity in the lab. SPE reactivity (experiment) was based on a mixed model, fitting self-esteem dynamics by an interaction of probability$_{Like}$ x valence. For visualization purposes, the y-axis represents the correlation between SPE condition and the predicted changes in self-esteem. The correlation is positive on average as SPE self-esteem reactivity increases with increasing SPEs. Each point represents the individual extracted correlation. B) Association of SPE reactivity on self-esteem during the experiment and in daily-life (EMA). Values are extracted comparable to A. SPE in EMA is based on an approximation taking the history of social experiences into account.

Discussion

This study investigated the impact of social experiences and social prediction errors on self-esteem in a sample spanning three decades of life (10-40 years). Employing both a controlled experiment and Ecological Momentary Assessment in daily life, we explored age-related differences in social self-esteem reactivity. Our experimental findings revealed a peak in late adolescence and a subsequent adult decline in the influence of social prediction errors (SPEs) on self-esteem. EMA analyses showed a linear decrease with age in the effects of pleasant social interactions and naturalistic social prediction errors on self-esteem. Importantly, social self-esteem reactivity in the controlled setting of our lab experiment was modulated by the influence of pleasant social interactions and naturalistic prediction errors on daily-life self-esteem, suggesting a link between experimental and daily-life self-esteem dynamics.

Our tightly controlled experimental paradigm provides an environment like those adolescents encounter on social media. We found that the overall expectation about being liked increased from late childhood to mid-adulthood, a pattern that aligns with a previous study conducted on a narrower age band (10-23 years) (19). Interestingly, adolescents' predictions were closer to the actual rate of receiving a like, whilst adults overestimated the probability of being liked. This suggests the presence of a 'positivity bias', a phenomenon previously similarly shown in adults (19). Positivity biases, also observed in other domains (e.g. memory recall or event attribution (35, 36)), might fulfil a self-protective function, e.g., in challenging situations (37). They are also associated with mental health (36, 38). Our research, in line with other studies (19, 38), indicates that these biases undergo development and are stronger in adults than in adolescents. Based on these results, one might speculate that a reduced (protective) positivity bias in adolescence might be associated with an increased vulnerability towards mental health problems. Indeed, a range of mental health issues that are related to lower self-esteem and problems in the social domain show their onset during adolescence (39). It is an interesting line of research for future studies to explore positivity biases in the social domain and their association with mental health problems, with a special emphasis on developmental aspects.

Besides testing age difference on expectations about being liked, our study was specifically designed to investigate dynamics underlying socially induced changes in self-esteem as well as age differences therein (spanning late childhood to mid-adulthood). We replicated previous research in adults showing that social prediction errors (i.e., whether a received like or dislike was expected or not), influence self-esteem (31, 32). Our results demonstrate that self-esteem reactivity to social prediction errors increased during adolescence and subsequently decreased during adulthood. In general, this highlights age-related changes in sensitivity to social signals that are informative about our self-worth. But why does self-esteem respond differently to unexpected social feedback at different ages? One proposal derived from the reinforcement learning literature is that adolescents tend to perceive their environment as more uncertain (40, 41). This has been shown to lead to increased (social) information seeking and more reliance on social information to resolve this uncertainty (13, 42). In a similar way, based on uncertainty about their own identity (43) and a socially highly modulable self-image (44), adolescents might rely more strongly on (external) social feedback to refine their understanding about themselves. Future studies should focus on whether increased SPE reactivity in self-esteem during adolescence/ emerging adulthood is indeed associated with increased uncertainty and information seeking about the environment and oneself.

Finally, on a more general level, these findings are consistent with previous research suggesting that adolescents show increased sensitivity to social evaluation (8, 10, 11) and social risks (45, 46). This sensitivity might be interpreted as adaptive on the one hand, as adolescents need to adjust to new environments while establishing their own social network. It is discussed that one reason for increased peer influence in adolescence might be a higher subjective value of peer acceptance, as well as higher subjective aversive value of peer rejection (45). Thus, unexpected social feedback (as it happens in our experiment and in daily life) might be perceived as more rewarding or aversive in adolescents than in adults. Accordingly, adolescents might integrate peer feedback faster into their self-esteem and adapt their behavior to meet new social demands, in the service of enhancing the probability of future peer acceptance. Indeed, susceptibility to peer influence predicted a higher degree of social integration in previous studies (13, 15). On the other hand, high social sensitivity in adolescents was shown to be associated with a higher load of depressive symptoms (47, 48), nominating social self-esteem reactivity as a potential catalysator for the development of mental health problems in the face of peer rejection or exclusion.

It should be subject of future research whether peer acceptance/rejection is perceived and integrated to the self-esteem differently across various ages of the "raters". In this study, age of the raters was not explicitly manipulated. In future studies, it would be interesting to contrast peer raters with raters from other age groups. This has been done in previous studies on social sensitivity in adolescence which suggested that to adolescents, the opinions and behavior of other teenagers matter more than the opinions of adults. (14, 15). Consequently, social prediction errors resulting from peer, rather than from adult social interactions, might be more influential to shape self-esteem in adolescents.

Surprisingly, while social self-esteem reactivity in daily-life decreased linearly from late childhood to mid-adulthood, in the lab the reactivity of self-esteem to SPE peaked later than expected, namely in late adolescence or emerging adulthood. Although our study cannot draw a clear conclusion about whether the age effects are linear or quadratic (which might also have methodological reasons caused by the high complexity of EMA models), it is interesting to discuss why heightened self-esteem reactivity seems to extend into young adulthood. Our initial hypothesis of an earlier peak or a decreasing trend (as we observed in daily-life) was based on studies showing increased social influence on adolescents compared to adults (13, 14, 49). At the same time, other findings focusing on sensitivity toward social rewards (self-reported via questionnaires) (50) could potentially justify also a later peak. Finally, a later peak aligns with a newer perspective that adolescence can be seen as a period extending into young adulthood with substantial socio-affective and neurobiological development up to the age of 24 or 25 (51-54). This phase of life, which is also labelled “emerging adulthood” by some authors (51), is further characterized by critical social challenges like moving away from home for the first time (51). We suggest that it is fruitful for future developmental studies to include a wider age range of adult participants beyond young adults at the beginning of their twenties. Interestingly, in many psychological studies, young adults (in their early 20s) are used as a reference population for adulthood as a whole. Our data, however, along with other studies in the social domain (e.g. (55)) rather imply that young adulthood represent a distinct transitional phase.

Previous longitudinal research (predominantly using questionnaires) has provided insight into a bidirectional relationship of social experiences and self-esteem. That is, social factors influence self-esteem and self-esteem influences social domains on larger time scales, (e.g. over a period of a year) (1, 2). That is, social experience influenced future self-esteem, and, in turn, self-esteem impacted future social experience. Here, we observed this bidirectional nature on much shorter timescales (of hours) in our EMA data (study 2), extending by making use of newer smartphone-based technologies. One direction of the effect, namely the effect of social experiences on self-esteem, is quite well established (and at the heart of the renowned sociometer theory (56)). EMA/diary studies demonstrated this direction over timeframes between 90 minutes and one day, albeit with rather small effect sizes (3, 57, 58).

The opposite effect direction of self-esteem on social experiences has not been demonstrated on shorter timescales in previous diary and EMA studies (3, 57, 58), possibly caused by a different way of measuring “social experiences”. Thus, our results uniquely highlight that self-esteem and social experiences influence each other in the short term, i.e., on a time scale of hours. Interestingly however, only the short-term social malleability of self-esteem showed a specific age effect, further emphasizing a dynamic and socially dependent nature of self-esteem during adolescent development. However, the question of different time scales in the modulation of self-esteem across development deserves further attention. Due to the widespread use of smartphones in adolescents and adults, EMA seems ideally suited to investigate this question in future studies (41). It is also a limitation of our study that social experiences were assessed by a single question asking about the pleasantness of the last social interaction. Future studies that focus on the relationship of self-esteem and social experiences should gain more information on the type of social interaction (e.g. virtually vs. in person, with friends vs. family, at school/work vs. in leisure time etc).

Interestingly, we found that self-esteem reactivity in daily-life moderated self-esteem reactivity observed in the experimental paradigm. That is, those who were particularly reactive towards social experiences in daily-life also showed enhanced social self-esteem reactivity in the lab underscoring the external validity of our experimental approach. Whilst in the controlled experimental setting we were able to manipulate expectations and ask participants about their predictions, this was not possible in our less controlled EMA assessment. Thus, it would be an interesting avenue to focus on the role of explicit social expectations in adolescents' everyday life. Which expectations do adolescents hold towards different social partners like peers, parents, siblings and relatives, teachers, therapists and how does their violation affect self-esteem? Which proportion of daily self-esteem variability can be explained by social prediction errors and what are non-social (or not directly social) sources of prediction errors (like daily achievements or stress (59, 60)) that drive self-esteem changes in daily life across development?

Our findings extend the understanding of how social prediction errors impact self-esteem from late childhood to mid-adulthood. They highlight that late adolescents and young adults are particularly sensitive to unexpected social feedback and that in daily-life, pleasant social interactions boost self-esteem more strongly in adolescents than in adults. Adolescence is marked by significant changes in self-image and the formation of new social networks, making individuals more open to integrating unexpected social feedback into their self-esteem. Tentatively, this might reflect an enhanced adaptivity of adolescents' self-image that is important in this (socially) highly dynamic phase of life in which a key developmental challenge is a massive reconfiguration of oneself in the context of new social environments. In times of exposure to constant social feedback, in daily life and via social media, understanding determinants of adolescent self-esteem is crucial to foster well-being and mental health for example by tailoring dedicated prevention programs for youth (61).

Materials and Methods

Recruitment

We included 141 participants whose age spanned late childhood over adolescence until middle adulthood (10-40 years, mean = 22.47, SD = 7.90). This comprised 89 participants who identified as female, 50 as male, 1 as diverse and 1 person who preferred not to state their gender. The age of the participants was approximately evenly distributed across the age range (Figure S1). Participants were recruited from databases at University Hospital of Würzburg and University of Dresden, as well as via flyers and posters and social media. 25 participants took part in a larger study, also including a paradigm in virtual reality and an extensive battery of cognitive experiments and questionnaires, results of which will be reported elsewhere. Four participants did not perform the social evaluation task, rendering n=137 datasets for the experimental task data. After applying exclusion criteria (see below), the EMA sample consisted of 115 participants (72 female participants, 41 male participants, 1 diverse person and 1 preferring not to state their gender; mean = 22.95, SD = 7.85). All analyses were calculated with the respective maximum number of available datasets. As gender effects in adolescent' self-esteem were found previously (25, 62), we additionally tested for gender effects (see Supplementary Results 3/Table S3; Supplementary Results 4/Table S4A). To account for individual differences in trait self-esteem (according to (31)), see Supplementary Results 2/Table S2).

Analysis of social evaluation task

Data preprocessing. Following an approach that was established in previous work with this experimental task (31, 32), we implemented a backfilling procedure for trials without self-esteem ratings as participants rated their self-esteem only every 2nd to 4th trial. This approach allows for an approximation of the cumulative impact of up to four feedback trials on self-esteem.

Data analysis. First, we run a generalized linear mixed logistic regression model to analyze whether a prediction of being liked by the raters was modulated by i) the probability of receiving a like (i.e., rater groups; rank order of group probabilities of liking/disliking others was learnt in the practice session) and whether ii) this was affected by age (linear and quadratic). We controlled for trait self-esteem, as in a previous study we found effects of trait self-esteem on the prediction of being liked (31). We also included the interaction of both age effects with the trial index (within rater groups, i.e. learning/adaptation based on repeated presentation of the color cue) to investigate whether the prediction changes during the experiment as a function of age.

> prediction (like vs. dislike) ~ $\text{probability}_{\text{Like}}$ + **age linear** * trial index (trials within rater groups) + **age quadratic** * trial index (repetitions within rater groups) + trait self-esteem+ ($\text{probability}_{\text{Like}}$|participant)

Our main aim – both in the experiment and in daily life – was to investigate the dynamics of self-esteem in response to social feedback, as well as age differences therein. A key hypothesis behind this experiment was that self-esteem changes both as a function of the feedback's valence (receiving a like vs. receiving a dislike) and expectation. In this experiment, a manipulation of the latter was realized by social prediction errors which are induced when a rater who belongs to a certain color-coded group gives feedback that deviates from the learned probability of receiving a like. That is, a positive prediction error is elicited if a participant receives a like by a rater who belongs to a group which was learnt to dislike most of the profiles, whilst negative prediction errors are generated when a participant receives a dislike by a rater of a group which was learnt to be benevolent beforehand. We thus analyzed how self-esteem (as the dependent variable) was modulated by the interaction between the probability of receiving a like (e.g., 0.15, 0.30, 0.70, or 0.85), and the valence of the feedback (+1 for like, -1 for dislike; no-feedback-trials excluded): self-esteem~$\text{probability}_{\text{Like}}$*valence. The interaction term captures the hypothesized changes in self-esteem in response to social prediction errors, i.e., higher self-esteem reactivity when one gets a like although the probability of receiving a like is small (high positive SPE), or one gets a dislike although the probability of receiving a like is high (high negative SPE). This stands in contrast to situations with low SPE when the received feedback is in line with the probability of receiving a like and thus expected. In the random effect structure, we included a random intercept of participants and a random slope of $\text{probability}_{\text{Like}}$ and valence as the participants' self-esteem reactivity might vary across conditions (valence+$\text{probability}_{\text{Like}}$|participant).

To probe our main hypothesis about age-related changes in the interplay of social feedback and self-esteem, we included interactions with age as a linear and quadratic (i.e., age²) term. We also included trait self-esteem as measured via the Rosenberg scale (63) as a covariate in all models, due to previous findings showing that this explains variance in the experiment,

> self-esteem ~ $\text{probability}_{\text{Like}}$ *valence***age linear** + $\text{probability}_{\text{Like}}$ *valence***age quadratic** + trait self-esteem + (valence+ $\text{probability}_{\text{Like}}$ |participant)

Ecological Momentary Assessment.

Assessing daily variability using EMA. We conducted an 8-day Ecological Momentary Assessment (EMA) using the MovisensXR app on participants' smartphones. The MovisensXR app is only available for Android phones, resulting in most participants being Android users. n=18 participants who had iOS phones were provided with study phones. EMA involved participants responding to prompts and questions throughout the day using the app. Certain questions were asked 10 times a day, with intervals of 1.5 hours between 8 AM and 9:30 PM. Some questions were asked only 4 times a day at 9:30AM, 3:30 PM, 6:30 PM, 9:30 PM. Among the broader set of questions asked (which will be reported elsewhere (64)), here we focus on two probes, (1) participants' momentary self-esteem ratings and (2) ratings of the pleasantness of participants' most recent social interactions. Self-esteem was measured by the question "How good do you feel about yourself right now?", asked 10-times a day. This question was designed to be identical to the one repeatedly asked during the experimental paradigm, ensuring consistency in the measurement of self-esteem. To capture the subjective pleasantness of social interaction, participants were asked to rate their experience of their last social contact "How pleasant was your last contact overall?" (i.e., at least 5 minutes of any kind of interaction), with responses collected 4-times a day.

Modelling daily-life social prediction errors. To mirror the experimental setting in the daily life, we calculated a new variable, namely dynamic social prediction errors based on EMA data. This variable constantly updated the social expectation, following an approach described in (34). This approach captures an idea that we build expectations about the pleasantness of social interactions by learning from past social interactions.

For each individual, we constructed a moving average of expectation of social pleasantness:

Expectation of social pleasantness$_t$ = expectation of social pleasantness$_{t-1}$ + alpha * daily-life SPE$_{t-1}$

where, alpha is a learning rate (recency parameter) fixed to 0.1 (based on (34)), which makes more recent outcomes more influential than earlier outcomes. The initial expectation was set to the sample mean rating of social pleasantness. The PE for an individual on a given rating was calculated as the difference between that prompt's expectation of social pleasantness (the moving average from the previous ratings) and the actual rating on trial t.

Daily-life SPE = expectation of social pleasantness$_{t-1}$ – social pleasantness$_t$

Modelling the association of self-esteem, pleasantness of social interaction and social prediction errors in daily-life.
To investigate the bidirectional relationship of self-esteem and social pleasantness in our EMA data, two time-lagged models using ratings at t-1 as predictors were constructed. Accordingly, two further time-lagged models were constructed including approximated prediction errors as independent variables instead of actual ratings at t-1. The first effect direction aimed to predict self-esteem using previous social pleasantness at timepoint t-1 (resp. social prediction error at t-1), while the second effect direction predicted social pleasantness at timepoint t using previous self-esteem rating at t-1 (resp. self-esteem prediction error at t-1). To adjust for neighboring constructs, all models incorporated the previous (i.e., t-1) ratings of loneliness, feeling accepted and loved, and the number of social contacts since the last prompt. Self-esteem/social pleasantness at t-1 was added to account for autoregression. To account for variations in response delays caused by a 30-minute time window and occasional missing data, the time difference to the last self-esteem rating (rated 10x/day) and the time difference to the last interaction rating (rated 4x/day) were included (delay$_{contact}$+ delay$_{self\text{-}esteem}$). The random effect structure consisted of a random intercept of the individual and a random slope of the day (day|participant). Note that only ratings obtained during the four time slots per day which included all questions (9:30 AM, 3:30 PM, 6:30 PM, 9:30 PM) were considered as dependent variables, while always the timewise closest possible previous rating was included as a predictor (approx. 1.5 hours before - 4.5 hours before).

To explore our main hypothesis about age-related changes in the mutual relationship of pleasantness of social interactions (and prediction errors therein) and self-esteem, we tested for a moderator effect of age by adding an interaction term with age to the two predictors of interest: pleasantness of the last social interaction (i.e, social pleasantness, resp. social prediction errors; t-1) and self-esteem at t-1 (resp. self-esteem prediction error). As the models were already very complex, we added age linear first and tested in the second step, whether the inclusion of the quadratic term improves the model fit. The latter was not the case, which is why we report only age effects considering linear changes. In the supporting information, the exact model terms are specified (Supplementary Methods 7).

Association between EMA and experiment
In this analysis step, we were interested in whether EMA measures reflect our observations in the lab experiment. We investigated whether daily-life self-esteem reactivity in response to i) the pleasantness of social interactions and to ii) naturalistic social prediction errors was associated with social prediction error reactivity in the experiment. This was done by allowing the 2-way interaction of valence x probability (capturing SPE reactivity in the experiment) to be moderated by an individual estimate capturing self-esteem reactivity measured by EMA. This estimate was calculated as a participant-specific random slope of previous social pleasantness, resp. previous

social prediction error, on self-esteem extracted from our EMA analysis. Such a random effect indicates individual deviations from the group mean in self-esteem reactivity and SPE self-esteem reactivity, i.e., the estimates represent participant-specific variation in the relationship between daily-life social pleasantness and self-esteem.
Thus, valence * $probability_{Like}$ interacted with individual random effects extracted from EMA data (resulting in a 3-way interaction) while self-esteem rating in the experiment was the dependent variable. The model syntax was as follows:

self-esteem~ **$probability_{Like}$ *valence*EMA random slope of self-esteem reactivity** + age linear + age quadratic + (valence+ $probability_{Like}$ |participant).

A significant 3-way interaction of $probability_{Like}$ *valence*EMA random slope of self-esteem reactivity would be evidence that SPE reactivity in the experiment is influenced by the degree of self-esteem reactivity in daily-life. Note that the EMA random slope of self-esteem reactivity was extracted from the introduced EMA model for self-esteem ratings, however including the random slope of social pleasantness at t-1 (resp. daily-life social prediction error at t-1).

Details on ethical information, experimental design, data preprocessing as well as analysis software, apparatus and sampling plan are provided in Supplementary Methods 1-6.

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Data and code availability: All materials, including the raw data, and analysis scripts, will be made public on https://osf.io upon acceptance of the paper.

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Supplement

Enhanced self-esteem reactivity in response to social prediction errors in adolescence.

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Supplementary Methods

1. Ethics information. The Ethics Committee of the University Hospital Würzburg approved all experimental procedures (#82/21-AM). The project was conducted in accordance with the revised current Declaration of Helsinki and the rules of Good Clinical Practice (GCP). Data storage is compliant with the provisions of the EU General Data Protection Regulation (GDPR). The participants (and their custodians for underaged participants) gave their informed consent and received financial compensation plus money gained in the experiment for their participation.

2. Social evaluation task. The experimental task was based on previous fMRI studies by Will et al. (1, 2). A demo version can be assessed here: https://kjppp-onlineresearch.ukw.de/AGReiter/profiles/profil.html?id=test (n= 112 participants completed the experiment online, and n=25 participants completed the experiment in person in the lab). The main objective was to simulate a social evaluation scenario with expected and unexpected positive and negative social feedback. We chose an experimental environment to resemble experiences people encounter on social media platforms where participants received likes or dislikes from their peers. Participants were asked (as a part of the cover story, see Figure 1A) to create their profiles at least two days before the experiment, and were told that other participants would evaluate these (i.e., like vs. dislike their profile). These profiles were set up to include positive statements about themselves, as well as some negative characteristics, fears, or aversions (to increase the plausibility of receiving both likes and dislikes). Importantly, the profile also included a photo from the participants which they could choose and upload themselves. Right before the social evaluation task started, participants were shown their profiles again, for them to recall their social appearance that should be evaluated by other participants. In reality, however, an unbeknownst to our participants, likes and dislikes were pre-determined as per our experimental conditions.

During the experiment, participants received positive feedback (in the form of a green “thumbs-up” symbol) on 80 trials, negative feedback (red “thumbs-down” symbol) on 80 trials, and neutral feedback (hidden) on 32 trials. Neutral trials were excluded from the analysis of SPE reactivity which core was the interaction: valence x $\text{probability}_{\text{Like}}$. The feedback came also from a total of 192 unique raters, evenly split between 96 males and 96 females. Participants were informed that raters belonged to four different color-coded groups based on their benevolence in terms of liking and disliking tendencies (see Figure 1B). That is, there was one group who gave positive feedback (i.e., a like) to 85% of profiles, the other groups approved at a rate of 70%, 30% and 15%. Participants were told that their general approval rate did not necessarily reflect how they would evaluate the participants profile specifically. The probabilities for receiving a like for the different groups were provided in general terms, without disclosing precise probabilities. Participants had to learn the rank order of the rater groups in a practice session, before beginning the experiment. Importantly, we set a learning criterion in this practice session, to ensure that in the main experiment, participants were aware of a groups’ tendency to like vs. dislike. The main experiment only started when participants correctly identified the more benevolent person (as inferred by the color-coding of their group) six times in six subsequent color pairs (minimum length of the learning block were 36 color pairs).

The main experiment was divided into three runs, with short breaks between each run. Each trial began with a fixation cross (700ms), followed by the question "Did this person like you?" (displaying also the name and an avatar of the rater, see Figure 1B). Participants had unlimited time to predict the rater’s feedback using "Yes" or "No" buttons. After making a prediction, the chosen answer remained on the screen for 2 seconds, while the unchosen option disappeared. Feedback by the rater, in form of a green thumb up, red thumb down, or a neutral grey circle, was displayed for 1 second, and accompanied by a sentence describing the feedback. The trial order and color cues indicating group membership were randomized across participants, with each rater group appearing once within every four trials. Participants were also asked to rate their current self-esteem every 2-4 trials (69-81 ratings in total), using a continuous scale with a slider labelled from "very bad" to "very good," corresponding to a scale of 0-100.

We did not exclude any experimental data prior to analyzing the data, like in previous work using this experiment (1, 2). Passing a learning criterion in the practice session was a prerequisite for the experiment to start (i.e., participants had to be able to identify the more benevolent rater group six times in six subsequent pairs). We also checked a couple of questions about participants' experience during the experiment. On a scale between 0 and 100, the experiment felt realistic on average of 57.39. There were eight participants who rated the realism of the experiment as less than 10. Excluding these participants from analyses of the experimental data did not change the main results. Realism ratings did not significantly correlate with age (r = 0.021, p-value=0.827).

3. Apparatus. Data collection and storage was implemented on servers hosted by the University Hospital Wuerzburg, Germany. We instructed participants to ensure they start the time-sensitive experiments only when seated in a quiet environment without potential interruptions, having the time window of approximately one hour available. The social evaluation task was implemented in jsPsych (4) and the social profile via SoSciSurvey (https://www.soscisurvey.de/). Participants filled besides the Rosenberg Score (5) and AIDA questionnaire (6). In the present study, only Rosenberg as a measure of trait self-esteem is included into the analyses as it corresponds to previous research (1, 2). The other scales will be reported elsewhere.

4. Sampling plan. We chose a sample size to exceed previous studies investigating age effects in adolescents and young adults, which regularly present a sample size around n=100 (7, 8). We also took our cue from (9) and aimed to exceed their sample size of 107 participants.

5. Analysis Software. We analyzed data from the experimental paradigm as well as EMA to answer the research questions. Our key interest was the interaction between self-esteem and pleasantness of social interactions. All data were analyzed using R (10). We employed linear mixed models (LMMs) and logistic mixed models from the 'lme4' (11) and 'afex' (12) package in R to analyze the data. Mixed models are a flexible and powerful statistical tool that allows for the incorporation of both fixed and random effects, making them suitable for analyzing repeated measures data. The package 'afex' allowed us to compute p-values (partly also F-values) from lme4 outputs. As a few models failed to converge using the default optimization parameter and default algorithm adapting the number of iterations, we increased the number of iterations to 10,000 for the non-converging models. Furthermore, we used the 'ggplot2' (13) and 'remef' (14) for plotting the data ('remef' is essential for extracting single effects out of the mixed models). 'Matrix' (15) package was loaded as it is a necessary dependency from 'lme4'.

6. Preprocessing Ecological Momentary Assessment Data. Before data analysis, several preprocessing steps were implemented to enhance data quality. Missing prompts, resulting from factors such as smartphones being switched off or compatibility issues with MovisensXR, were manually coded as missing value to allow for the calculation of the completion rate. Additionally, a thorough check was conducted to identify and exclude a minimal number of technical entry errors, such as double entries per prompt or a delay of less than 30 min between prompts. Subsequently, we excluded all days on which participants completed less than 2 of 10 prompts (for questions asked 10 times/day) and less than 1 of 4 trials (for questions asked 4 times/day). After having removed such days with poor response rates, we further excluded participants with an overall response rate below 50% and participants who completed less than three days. Taken all exclusion criteria together, we excluded 24 participants from analyses involving EMA. The completion rate (considering all 10 prompts per day) was 73.93%, and this correlated positively with age (ES=0.034, SE=0.012, t-value=2.636, p-value=0.010). Delays between ratings correspondingly decreased with increasing age (10x/day ratings: median of delays=1.64 hours, min=0.56h, max=52.44h, age effect $\text{p-value}_{10x/day}$=0.007; 4x/day ratings: median of delays=4.50 hours, min=0.56h, max=62.24h, age effect $\text{p-value}_{4x/day}$=0.035).

To analyze the general properties of our EMA dataset, we computed individual means and standard deviations for self-esteem and the pleasantness of social interactions. Notably, we considered averaged daily means, resp. standard deviations, recognizing potential variability between individual days. Using simple linear regressions, we tested whether the mean and standard deviation of self-esteem and social pleasantness varied with age. In the analysis of social pleasantness, we additionally accounted for the number of social contacts. Besides, we conducted a linear regression focusing on age effects in completion rates. Finally, we explored age effects on the delays between prompts, employing a mixed model clustered by participants.

As a last step of the preprocessing procedure, we created variables t-1, by shifting responses by one prompt forward for the purpose of a time-lagged analysis. This allowed us to calculate the effect of the previous rating at time point t-1 on the rating at the very prompt (t) in our models (see below).

7. Model terms for time-lagged analyses using EMA data

i. **Social pleasantness → self-esteem in everyday life:**
self-esteem (t) ~
self-esteem (t-1) *age linear + social pleasantness (t-1) *age linear+
*[self-esteem (t-1) *age quadratic + social pleasantness (t-1) *age quadratic+]*
loneliness (t-1) + feeling accepted & loved (t-1) + number of contacts (t-1) +
$\text{delay}_{\text{social pleasantness t-1}}$ + $\text{delay}_{\text{self-esteem t-1}}$ +
(day|participant)

ii. **Self-esteem → social pleasantness in everyday life:**
social pleasantness (t) ~
social pleasantness (t-1) * age linear + self-esteem (t-1) *age linear +
*[social pleasantness (t-1) * age quadratic + self-esteem (t-1) *age quadratic +]*
loneliness (t-1) + feeling accepted & loved (t-1) + number of contacts (t-1) +
$\text{delay}_{\text{social pleasantness t-1}}$ + $\text{delay}_{\text{self-esteem t-1}}$ +
(day|participant)

iii. **SPE → self-esteem in everyday life:**
self-esteem (t) ~ **PE self-esteem (t-1) *age linear +**
PE social pleasantness (t-1, i.e. SPE_{t-1}) *age linear +
*[PE self-esteem (t-1) *age quadratic +*
*PE social pleasantness (t-1, i.e. SPE_{t-1}) *age quadratic +]*
PE loneliness (t-1) + PE feeling accepted & loved (t-1) + PE number of contacts (t-1) +
$\text{delay}_{\text{social pleasantness t-1}}$ + $\text{delay}_{\text{self-esteem t-1}}$ +
(day|participant)
where PE = is a prediction error ranging from -100 to 100 for questions scored on a scale between 0 and 100. If SPE>0, social pleasantness is expected to exceed individual self-esteem, and if SPE<0, it is expected to underestimate individual moving average in social pleasantness, i.e. a positive effect of SPE on self-esteem is hypothesized.

iv. **Self-esteem prediction error → social pleasantness in everyday life:**
social pleasantness (t) ~ **PE self-esteem (t-1) *age linear +**
PE social pleasantness (t-1, i.e. SPE_{t-1}) *age linear +
*[PE self-esteem (t-1) *age quadratic +*
*PE social pleasantness (t-1, i.e. SPE_{t-1}) *age quadratic +]*
PE loneliness (t-1) + PE feeling accepted & loved (t-1) + PE number of contacts (t-1) +
$\text{delay}_{\text{social pleasantness t-1}}$ + $\text{delay}_{\text{self-esteem t-1}}$ +
(day|participant)
where the definition of prediction errors (PE) is analogous to the previous analysis, i.e. current self-esteem exceeds or underestimate individual moving average in self-esteem.

All predictors were z-transformed using the default scale() function in R. Age was z-transformed before entering the model. After running the described models, we tested whether the fit improves when adding the quadratic age term (age^2), i.e. adding the part in the square bracket to the model term.

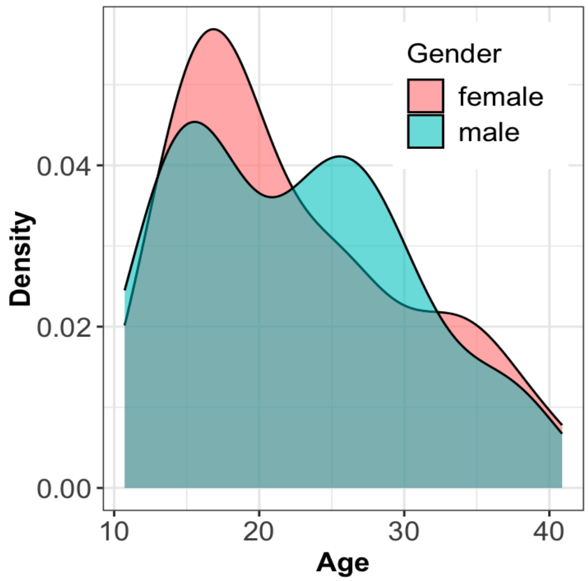

Figure S1. *Distribution of male and female participants across the age range. Density plot represents an alternative to a histogram especially suiting for continuous predictors. As the age comprises decimal places it fits better for mapping the distribution. The function is used in its default mode.*

Supplementary Results

1. Learning by age within rater groups. In a post-hoc analysis we calculated model that allowed for the moderation of the trial x age interactions by the rater group (model term: *prediction of being liked ~ trial number * age linear * probability$_{like}$ + trial number * age quadratic * probability$_{like}$ + trait self-esteem + (probability$_{like}$|participant))*. This step aimed at exploring whether the observed age effects were pronounced rather for the benevolent or unfriendly rater groups. While the overall age effect on positivity bias remained unmoderated by rater groups (FE=-0.063, SE=0.161, p-value=0.697), the trend of increasing adaptation of predictions with increasing age was particularly pronounced for the less benevolent groups (FE=0.046, SE=0.020, p-value = 0.025, see Table Table S1 and Figure S2).

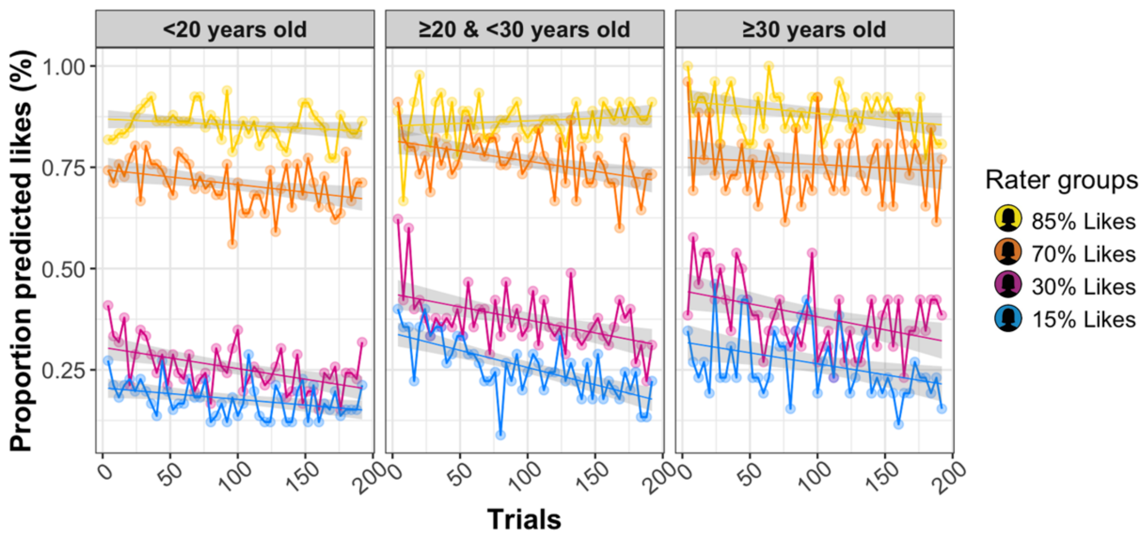

Figure S2*. Learning by age within rater groups. The predictions of receiving a like are aggregated across trials (trial number within rater groups), rater groups and for visualization purposes across three age groups (per decade). Each point represents the aggregated mean. The lines and their standard errors represent group specific trends across the experiment. They are generated automatically by the function geom_smooth() in ggplo2. With increasing age, the decrease across trials got greater for the less benevolent groups.*

Table S1. Learning by age within rater groups

Predictor	FE	SE	p-value
Intercept	**0.451**	**0.128**	**<0.001**
Probability$_{Like}$	**1.918**	**0.202**	**<0.001**
Age linear	**0.205**	**0.101**	**0.043**
Trial number (within rater group)	**-0.174**	**0.025**	**<0.001**
Age quadratic	-0.178	0.096	0.064
Trait self-esteem	**0.393**	**0.090**	**<0.001**
Probability$_{Like}$ x trial number	**0.110**	**0.026**	**<0.001**
Age linear x trial number	-0.035	0.020	0.074
Age_quadratic x trial number	0.013	0.019	0.499
Probability$_{Like}$ x age linear	-0.062	0.162	0.699

$\text{Probability}_{\text{Like}}$ x age quadratic	0.093	0.152	0.540
$\text{Probability}_{\text{Like}}$ x age linear x trial number	**0.046**	**0.020**	**0.026**
$\text{Probability}_{\text{Like}}$ x age quadratic x trial number	-0.036	0.020	0.067

Note: $\text{Probability}_{\text{Like}}$ (numeric predictior representing rater groups), Age linear (exact decimal number based on the date of participation and the birthday) and trial number (repetitions within rater group) were normalized by the function scale(). Age quadratic resulted from squaring the normalized linear age.

2. Effect of trait self-esteem on learning. Instead of age, we interacted trait self-esteem with trial number (i.e. again repetitions within rater groups) to test whether the adaptation across the experiment was modulated by trait self-esteem (*prediction of being liked ~ trial number * trait self-esteem + probability$_{Like}$ + age linear + age quadratic + (probability$_{Like}$ |participant)*). As participants overall reduced their expectation about receiving a like across the experiment (effect of trial number; FE=0.167, SE=-0.017, p-value=<0.001), this effect tended to be reduced for participants with high trait self-esteem (interaction trial number x trait self-esteem; FE=0.032, SE=0.018, p-value=0.068, see Table S2).

Table S2. Effect of trait self-esteem on learning

Predictor	FE	SE	p-value
Intercept	**0.454**	**0.128**	**<0.001**
Trial number (within rater group)	**-0.167**	**0.017**	**<0.001**
Trait self-esteem	**0.393**	**0.090**	**<0.001**
Age linear	**0.206**	**0.101**	**0.042**
Age quadratic	-0.177	0.096	0.066
$\text{Probability}_{\text{Like}}$	**2.006**	**0.141**	**<0.001**
Trait self-esteem x trial number	0.032	0.018	0.068

Note: $\text{Probability}_{\text{Like}}$ (numeric predictior representing rater groups), Age linear (exact decimal number based on the date of participation and the birthday) and trial number (repetitions within rater group) were normalized by the function scale(). Age quadratic resulted from squaring the normalized linear age.

3. Effect of gender on expectation about being liked and learning. Finally, instead of age, we included participants' and raters' gender interacting with the trial number (*prediction of being liked ~ trial number * gender participant + trial number * gender rater + probability$_{Like}$ + age linear + age quadratic + (probability$_{Like}$ |participant)*). We found that female participants predicted substantially less to receive a like (FE=-0.289, SE=0.088, p-value=0.001). The adaptation of the expectation did not significantly change by gender (interaction trial number x participant gender: FE=-0.019, SE=0.018, p-value=0.292; Table S3).

Table S3. Effect of gender on learning

Predictor	FE	SE	p-value
Intercept	**0.552**	**0.125**	**<0.001**
Trial number (within rater group)	**-0.158**	**0.018**	**<0.001**
Gender participant	**-0.289**	**0.088**	**<0.001**
Gender rater	0.010	0.018	0.575
Age linear	**0.209**	**0.098**	**0.033**
Age quadratic	-0.180	0.092	0.051

Trait self-esteem	**0.350**	**0.089**	**<0.001**
$\mathbf{Probability_{Like}}$	**2.001**	**0.141**	**<0.001**
Gender participant x trial number	-0.019	0.018	0.292
Gender rater x trial number	-0.003	0.018	0.872

Note: $Probability_{Like}$ (numeric predictior representing rater groups), Age linear (exact decimal number based on the date of participation and the birthday) and trial number (repetitions within rater group) were normalized by the function scale(). Age quadratic resulted from squaring the normalized linear age. We excluded participant not defining themselves as males or females from this analysis.

4. Post-hoc analyses on self-esteem dynamics in the experiment. Post-hoc analyses adding the effect of gender of the participant and gender of the raters revealed no significant effects. The correctness of the prediction overall increased the momentary self-esteem (main effect) but did not affect either the SPE, nor the valence reactivity (Table S4).

Table S4A. *Extract from post-hoc model testing gender & correctness effects.*

Predictor	*F*	*df*	*p-value*
Gender participant	0.06	124.95	0.800
Gender rater	0.33	20402.94	0.567
Correctness	**75.41**	**12437.09**	**<0.001**

Note: model formula was defined as followed: *self-esteem ~ $probability_{Like}$ *valence****age linear** + *$probability_{Like}$ *valence****age quadratic** + *trait self-esteem + gender participant + gender rater + correctness + (valence+ $probability_{Like}$ |participant)*

Table S4B. *Effect from post-hoc model testing the effect of correctness on valence reactivity and SPE reactivity.*

Predictor	*F*	*df*	*p-value*
Valence x correctness	0.03	14127.75	0.860
Valence x $probability_{Like}$ x correctness	0.58	13812.70	0.448

Note: model formula was defined as followed: *self-esteem ~ $probability_{Like}$ *valence****correctness** *+ trait self-esteem + (valence+ $probability_{Like}$ |participant)*

5. Social expectation dynamics as a function of self-esteem. As bidirectional interaction between self-esteem and social interaction is hypothesized, we tested on the experimental data whether ratings of self-esteem affect following expectation about being liked. We analyzed only trials immediately following a self-esteem rating and predicted expectation about being liked or disliked (timepoint t) by the previous self-esteem rating (t-1). In addition, we allowed interaction of previous self-esteem with age (as we know that the positivity bias linearly increased) and the rater groups (as these were decisive for building expectations). As the output was binomial, we calculated a mixed logistic regression.
*Prediction (like/dislike) ~ $self\text{-}esteem_{t-1}$ * $probability_{Like}$ * age linear + ($probability_{Like}$ | participant)*

We found that previous momentary self-esteem was positively associated with the upcoming expectation. That means, given high self-esteem rating, the upcoming expectation improved (SE=0.118, SE=0.055, p-value=0.033, see Table S5). Moreover, rater group and previous self-esteem interacted without showing any age effect. Irrespective of age also, the expectation about being liked not only improved with the benevolence of the rater group, but multiplicatively more so if the previous self-esteem was also high (FE=0.185, SE=0.061, p-value=0.002, see Table S5 & Figure S4). Based on this we can conclude that previous self-esteem affect expectation differently for benevolent and unbenevolent rater groups. Deducing from the figure, high previous self-esteem allows higher differentiability of the own expectation.

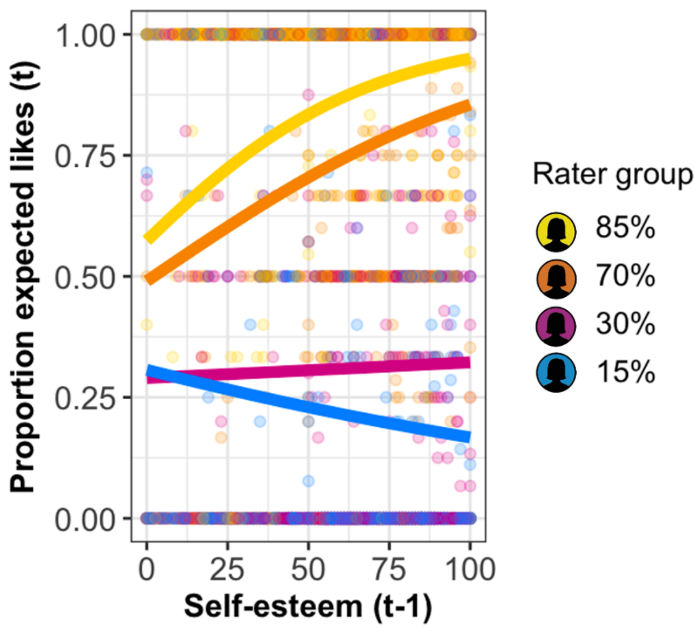

Figure S4. *Prediction about being liked was influenced by previous self-esteem ratings. The direction of the effect was dependent from the rater group (self-esteem$_{t-1}$ x probability$_{Like}$ interaction). Dots aggregated by participant, previous self-esteem$_{t-1}$ and rater group.*

Table S5. Social expectation dynamics as a function of self-esteem

Predictor	FE	SE	p-value
Intercept	**0.267**	**0.102**	**0.009**
Self-esteem$_{t-1}$	**0.118**	**0.055**	**0.033**
Probability$_{Like}$	**2.113**	**0.142**	**<0.001**
Age linear	0.142	0.102	0.161
Self-esteem$_{t-1}$ x Probability$_{Like}$	**0.185**	**0.061**	**0.002**
Self-esteem$_{t-1}$ x Age linear	0.065	0.057	0.257
Probability$_{Like}$ x Age linear	0.015	0.141	0.913
Self-esteem$_{t-1}$ x Probability$_{Like}$ x Age linear	0.002	0.063	0.971

Note: Probability$_{Like}$ (numeric predictior representing rater groups), age linear (exact decimal number based on the date of participation and the birthday) and self-esteem ratings were normalized by the function scale().

6. Mean level and variability in social pleasantness and self-esteem in everyday life across the investigated age range. On a scale ranging from 0 to 100, participants indicated their momentary self-esteem (averaged daily mean =66.76, SD$_{mean}$=13.87, rated 10x/day, averaged daily variability=11.03, see Figure S3) as well as the pleasantness of the last social interaction; (averaged daily mean = 72.29, SD$_{mean}$=10.93, rated 4x/day, averaged daily variability= 12.29, see Figure S3). Both, averaged daily means and standard deviations of self-esteem, correlated significantly with trait self-esteem (Rosenberg scale), validating the EMA ratings: r=0.58 (p<0.001) for means, r=-0.34 (p<0.001) for SDs. Therefore, participants with low trait self-esteem not only feel bad about themselves in the everyday life but also show stronger fluctuation. In addition, mean self-esteem assessed by EMA correlated with mean self-esteem ratings assessed during the experiment (r=0.61, p<0.001). However, the variability of EMA and experimental ratings were not correlated (r=0.04, p=0.687), perhaps reflecting the fact that EMA operates on different timescales than our experimental task, and that self-esteem dynamics in real-life are influenced not only by social feedback (as in our controlled experimental setting), but also by other momentary inputs (non-social outcomes, internal thoughts and feelings).

Social pleasantness (ES=-3.317, SE= 1.210, p-value=0.007, see Figure S3), but not self-esteem (ES=-1.874, SE=1.572, p-value=0.236, see Figure S3) measured via EMA decreased linearly with age. Also, the variability of ratings increased with age for social pleasantness (ES=1.161, SE=0.549, p-value=0.037, see Figure S3) but not significantly for self-esteem (ES=0.244, SE=0.582, p-value=0.676, see Figure S3). However, age effects in mean level and variability of social pleasantness were not significant anymore when adjusting for the number of contacts (all p's>.109). This speaks to the notion that differences in the number of social contacts explain age differences in social pleasantness.

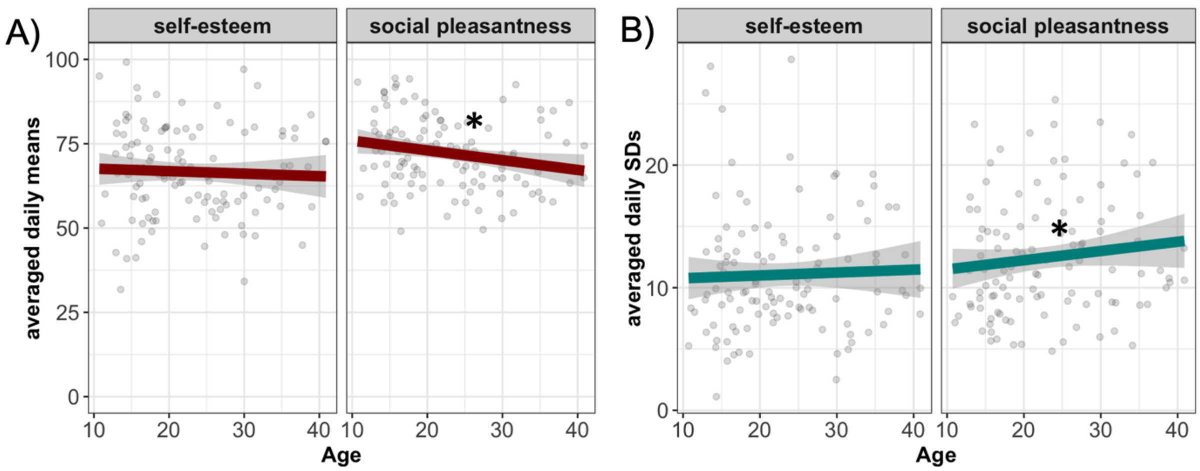

Figure S3. *Real-life ratings across the investigated age range. A) averaged daily means representing levels of self-esteem and social pleasantness. The asterisk indicates significant age effects. B) averaged daily standard deviations representing within-person variability of self-esteem and social pleasantness. The asterisks indicate significant age effects.*

7. Time-sensitive analysis (EMA). As self-esteem was sampled more frequently (1.5-hour intervals instead of approx. 4.5-hours interval), we tested, as a control analysis, whether the results of reciprocity between self-esteem and social pleasantness held if we omitted all self-esteem ratings sampled within the approx. 4.5-hour intervals. This means that only data collected during the 4x/day intervals were considered, like the previous ratings at t-1. However, this did not change the finding that self-esteem significantly influenced the pleasantness of social interaction (FE=1.196, SE=0.498, p-value=0.016). It is also interesting to note that self-esteem assessed at these less frequent time points tends to modulate social pleasantness more for adolescents than for adults (FE=-0.892, SE=0.462, p-value=0.053). This highlights the importance of timing before generalizing the findings.

8. SPEs explain changes in self-esteem better than just valence. Es it is conceivable that previously rated social pleasantness still outperforms the prediction strength of social prediction errors, we tested a model including both. The model term was composed as follows (simplified combination of models i and iii in Supplementary Methods 7):

self-esteem (t) ~ social pleasantness (t-1) * age linear + self-esteem (t-1) *age linear +
PE self-esteem (t-1) *age linear + PE social pleasantness (t-1, i.e. SPE_{t-1}) *age linear +
$delay_{social\ pleasantness\ t-1}$ + $delay_{self\text{-}esteem\ t-1}$ + (1|participant)
(random slope was removed due to singular fit of the model)

Besides self-esteem being predicted by previous self-esteem and the extent to which the previous self-esteem was unexpected, only daily SPE_{t-1} (FE=1.093, SE=0.520, p-value=0.036), not social $pleasantness_{t-1}$ (FE=-0.274, SE=0.616, p-value=0.657) significantly affected self-esteem at timepoint t.

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