

Promoting Psychological Resilience and Well-Being in Youth With a Smartphone-Based Ecological Momentary mHealth Intervention: Secondary Analysis of a Micro-Randomized Trial

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Abstract

Background: Young individuals have been facing a multitude of crises in the past years, which may be associated with negative mental health outcomes. Interventions to mitigate the negative impact and promote mental well-being are necessary. Ecological momentary interventions (EMIs) may be a promising tool for promoting mental well-being as they allow to target resilience and other protective factors in daily life.

Objective: In this secondary analysis of a micro-randomized trial, we explored proximal effects of a compassion-focused smartphone-based digital training for young people applying principles and techniques of EMI (the AI4U training) on momentary outcomes of mental well-being.

Methods: Participants aged 14 to 25 years completed up to six ecological momentary assessments (EMA) per day to measure their momentary mental well-being (ie, positive affect, negative affect, and stress) during the 30-day AI4U training phase. Some EMA prompts triggered EMI components to promote their momentary resilience and well-being. Proximal effects of initiating EMI components on outcomes assessed at the next time point were analyzed using multilevel modelling. Moderation and mediation analyses were applied to investigate the potential moderating effect of momentary affect and stress at the time of EMI initiation and to explore change in momentary resilience as a mediator of the effect of EMI initiation on changes in momentary affect and stress.

Results: 170 individuals completed 13059 EMA prompts and initiated 6667 EMI components. No evidence was found that momentary outcomes of mental well-being at a time point differed depending on whether an EMI component was initiated at the previous time point vs. when no EMI component was initiated (positive affect: $b=0.00$, CI -0.04 to 0.04; negative affect: $b=-0.01$, CI -0.05 to 0.03; stress: $b=0.01$, CI -0.03 to 0.05). There was no strong difference in the magnitude of this effect when momentary mental well-being at the time of EMI initiation was high vs. low (positive affect: $b=0.07$, 95% CI=-0.00 to 0.15; negative affect: $b=-0.01$, CI=-0.09 to 0.06; stress: $b=0.07$, CI=-0.01 to 0.15). Changes in momentary resilience did not mediate

the effect of EMI component initiation on changes in momentary mental well-being (positive affect: $b=0.01$, $CI=-0.01$ to 0.02 ; negative affect: $b=0.00$, $CI=-0.01$ to 0.00 ; stress: $b=0.00$; $CI=0.00$ to 0.00).

Conclusions: This secondary analysis investigated potential mechanisms of how a digital training leads to long-term improvement of distal outcomes. The analysis contributes to the research in the field by serving as a basis for future investigations on the momentary effects of EMI components.

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Original Manuscript

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ABSTRACT

Background: Young individuals have been facing a multitude of crises in the past years, which may be associated with negative mental health outcomes. Interventions to mitigate the negative impact and promote mental well-being are necessary. Ecological momentary interventions (EMIs) may be a promising tool for promoting mental well-being as they allow to target resilience and other protective factors in daily life.

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Methods: Participants aged 14 to 25 years completed up to six ecological momentary assessments (EMA) per day to measure their momentary mental well-being (ie, positive affect, negative affect, and stress) during the 30-day AI4U training phase. Some EMA prompts triggered EMI components to promote their momentary resilience and well-being. Proximal effects of initiating EMI components on outcomes assessed at the next time point were analyzed using multilevel modelling. Moderation and mediation analyses were applied to investigate the potential moderating effect of momentary affect and stress at the time of EMI initiation and to explore change in momentary resilience as a mediator of the effect of EMI initiation on changes in momentary affect and stress.

Results: 170 individuals completed 13059 EMA prompts and initiated 6667 EMI components. No evidence was found that momentary outcomes of mental well-being at a time point differed depending on whether an EMI component was initiated at the previous time point vs. when no EMI component was initiated (positive affect: $b=0.00$, CI -0.04 to 0.04; negative affect: $b=-0.01$, CI -0.05 to 0.03; stress: $b=0.01$, CI -0.03 to 0.05). There was no strong difference in the magnitude of this effect when momentary mental well-being at the time of EMI initiation was high vs. low (positive affect: $b=0.07$, 95% CI=-0.00 to 0.15; negative affect: $b=-0.01$, CI=-0.09 to 0.06; stress: $b=0.07$, CI=-0.01 to 0.15). Changes in momentary resilience did not mediate the effect of EMI component initiation on changes in momentary mental well-being (positive affect: $b=0.01$, CI=-0.01 to 0.02; negative affect: $b=0.00$, CI=-0.01 to 0.00; stress: $b=0.00$; CI=0.00 to 0.00).

Conclusions: This secondary analysis investigated potential mechanisms of how a digital training leads to long-term improvement of distal outcomes. The analysis contributes to the research in the field by serving as a basis for future investigations on the momentary effects of EMI components.

Keywords: ecological momentary assessment, experience sampling method, ambulatory assessment, ecological momentary intervention, just-in-time adaptive intervention, digital training, mobile health,

digital health, mental health, affect, adolescent, mobile phone



INTRODUCTION

Young individuals are a vulnerable group at risk for mental health conditions, as many mental health conditions first appear in childhood or adolescence [1, 2] and contribute significantly to disease burden of young people [3]. In the past years, young individuals have also been facing a multitude of crises such as the COVID pandemic and the climate crisis, which are associated with negative mental health outcomes [4]. For instance, a systematic review showed that the prevalence of depressive and anxiety symptoms among children and adolescents increased during the COVID-19 pandemic compared to prepandemic numbers [5]. Hence, there is an urgent need for easily accessible measures of mental health promotion in youth.

A promising approach involves targeting psychological resilience, as numerous studies have demonstrated a strong association between higher levels of resilience and improved mental health and well-being [6, 7]. Psychological resilience can be defined as the ability to deal with adversity in different areas of life while maintaining focus on one's personal goals [8, 9]. It is therefore an especially important capability to protect mental health in times of crisis. Different approaches exist to increase resilience, such as interventions based on cognitive behavioral therapy (CBT) or mindfulness [10]. However, these interventions are often associated with high costs and time investment [10]. In addition, young people can be hard to reach for interventions aimed at improving their mental well-being due to for example stigma or low mental health literacy [11].

Digital interventions have the potential to increase the accessibility of mental health services for young people [12] and to reduce costs [13]. A review showed that digital resilience programs have positive effects on for example psychological distress and positive mental health in non-clinical adult populations [14]. A specific type of digital interventions are ecological momentary interventions (EMIs), which deliver intervention components in real time via digital platforms and apps and can therefore be directly incorporated in everyday life [15-17]. They can be tailored to the specific needs of an individual and to the requirements of a given context [18, 19] based on intensive longitudinal data collected using ecological momentary assessment [EMA; 20, 21-23]. A review found that EMI based on CBT can improve mental well-being and reduce symptoms of mental health conditions in both healthy and clinical samples [24]. Another review suggested that EMIs targeting outcomes of mental health and positive psychological well-being have small to medium-sized effects, but that the low quality of the available studies requires more rigorous evidence generated by randomized controlled trials [RCT; 24]. A recent RCT has shown that a mindfulness-based EMI led to a reduction in anxiety and depressive symptoms in individuals with generalized anxiety disorder after two weeks of training [25]. In another RCT, participants' self-esteem after using the SELFIE intervention for 6

weeks was on average higher both at post-intervention and at 6-month follow-up compared to the control condition that received care as usual [21]. An EMI with compassion-focused exercises (EMIcompass) improved quality of life and stress-reactivity after 6 weeks of training in a feasibility RCT [20].

Despite the evidence on the effects of EMIs for improving outcomes of mental health and psychological well-being, so far, it is unclear how exactly EMIs yield these beneficial effects. Understanding the exact mechanisms through which EMI work would offer the opportunity to further adapt EMIs to increase their efficacy. One way to elucidate this further is to shed light on the immediate effects of individual EMI components, often referred to as proximal effects [26]. Proximal effects of EMIs were reported in previous studies: An EMI targeted to reduce smoking had a proximal effect on negative affect [27]. Furthermore, the results of a process evaluation of the EMIcompass intervention indicated that strengthening the soothing system may have accounted for the initial signals of reduced stress reactivity and improved quality of life that were observed in the feasibility RCT [20, 28]. The soothing system refers to an emotion regulation system associated with feelings of safeness and inner warmth which compassion-focused therapy aims to activate by fostering compassion and self-compassion [29]. The EMIcompass intervention included exercises such as compassionate imagery and mindful breathing to help participants to activate the soothing system in stressful situations. This ability can be seen as a coping mechanism that supports individuals to better deal with adverse situations and therefore may reflect resilience [28]. However, to enhance the robustness of these findings, which were based on the participants' subjective experiences, additional quantitative methods need to be employed to investigate proximal effects of compassion-focused EMIs on mental well-being and resilience. Using data acquired in daily life by EMA as part of EMIs, for example on affect or stress, may elucidate the proximal effects of individual EMI components and, hence, offer an especially promising avenue for investigating mechanisms by which long-term training effects are obtained. In a subsample of participants with early mental health problems, initial signals for proximal effects of the EMIcompass intervention on negative affect, stress and stress reactivity were found [30]. In contrast that study, the living lab AI4U for digital personalized mental health promotion in adolescents and young adults was not limited to adolescents experiencing mental health conditions. It applied both EMA and EMI as part of a digital mobile health (mHealth) training – the *AI4U training* - and therefore allows to investigate proximal effects of EMI components on momentary indicators of well-being. Using three micro-randomized controlled trials (MRTs), the living lab AI4U investigated the effects of applying machine learning (ML) algorithms to deliver EMI components [31]. The EMI applied in the AI4U training was partly

based on the EMI used in previous research [20, 21, 28, 32] and included brief EMI components amenable to be delivered and integrated in daily life. A comprehensive description of the individual components comprising the EMI is reported elsewhere [31].

The aim of this secondary analysis of data collected as part of the AI4U living lab was to investigate proximal effects of completing EMI components, that is, effects of EMI components on outcomes assessed at the next time point using EMA in youth from the general population and family counselling services. It was expected that completing an EMI component will improve mental well-being, that is, positive affect, negative affect and stress at the subsequent EMA time point. The effect was expected to be greater when mental well-being at the time of completing the EMI was low. In addition, it was assumed that the effect of completing EMI components on mental well-being will be partially mediated by an increase in momentary resilience following the initiation of the EMI. Therefore, the following three hypotheses were tested:

First, it was hypothesized that i) positive affect at t_n will be higher following the initiation of an EMI component at t_{n-1} compared with non-initiation of an EMI component at t_{n-1} , ii) negative affect and iii) perceived stress at t_n will be lower following initiation of an EMI component at t_{n-1} compared with non-initiation of an EMI component at t_{n-1} .

Second, it was hypothesized that the magnitude of this difference in i) positive affect, ii) negative affect, and iii) perceived stress between initiation and non-initiation of EMI components at t_{n-1} will be modified by levels of i) positive affect, ii) negative affect, and iii) perceived stress at t_{n-1} such that the magnitude of this difference will be greater following i) low levels of positive affect, ii) high levels of negative affect, and iii) high levels of perceived stress at t_{n-1} compared with i) high levels of positive affect, ii) low levels of negative affect, and iii) low levels of perceived stress at t_{n-1} .

Third, the effect of initiating an EMI component at t_{n-1} on i) positive affect, ii) negative affect, and iii) stress at t_n was hypothesized to be mediated by an increase in momentary resilience from t_{n-1} to t_n , while controlling for i) positive affect, ii) negative affect, and iii) stress at t_{n-1} .

METHODS

Study Design

The living lab AI4U carried out four transdisciplinary projects involving direct participation of relevant stakeholders, users from the target population and an interdisciplinary research group. The current study draws on data collected using EMA during three within-subject MRTs [MRT; 33, 34] conducted consecutively as part of the second transdisciplinary AI4U project to examine proximal effects of initiating an EMI component on indicators of mental well-being. Findings on the primary outcome of these MRTs and other

transdisciplinary projects of the living lab AI4U are published elsewhere [31, 35-37]. These secondary analyses were preregistered at the open science framework [38] after data collection was completed. Deviations from the preregistration can be found in Supplement 1. The study was approved by the Medical Ethics Review Committee II at Heidelberg University (Medical Faculty Mannheim; Ref. No. 2022-550).

Each participant took part in a 90-min training session with a trained study team member that provided guidance on content and structure of the training before starting the 40-day AI4U training, consisting of a 10-day introductory phase and a 30-day training phase, on a study smartphone. The AI4U training consisted of an EMI administered using a smartphone-based app (movisensXS app, Version 1.6.2-beta.4, movisens GmbH, Karlsruhe, Germany) for adaptive real-time and real-world transfer of mental health promotion principles into daily life and was supported by sessions with counsellors for those who were receiving help from educational counselling services at the time of the study. During the AI4U training, participants had continuous access to the web-based AI4U dashboard, which displayed summary statistics of the collected EMA data in various charts and tables, and allowed them to self-monitor assessed EMA variables in real-time. Members of the study team contacted each participant up to two times via phone during the training to address questions and encourage consistent app use. After the AI4U training, participants were invited to a final review session. Data on distal outcomes were collected at baseline and at post-intervention. Full details on the procedure and on distal mental health outcomes can be found elsewhere [31].

Participants

Participants were recruited from the general population in Germany between July 2022 and June 2024 through a combination of methods, including a call for participation posted on the project website, referrals from counsellors, and information events held in community settings, such as youth clubs. The inclusion criteria were: age between 14-25 years, willingness to participate in the ecological momentary intervention, ability to give written informed consent independently or through a legal guardian. The exclusion criteria were: insufficient command of German, current diagnoses of any mental health condition, current psychiatric or psychotherapeutic treatment, acute suicidality. Participants were compensated with 70€-120€ for their time, depending on how many times they interacted with the AI4U training.

Intervention

The AI4U training phase consisted of a 10-day introductory phase, during which the different EMI components were successively introduced, and a subsequent 30-day training phase. Proximal outcomes were assessed using EMA. The current study focusses on the proximal effects of EMI component initiation vs. non-initiation on momentary indicators of well-being during the training phase. The main findings of the primary analysis are described elsewhere [31].

The EMI used three types of delivery schemes: enhancing, consolidating, and interactive/adaptive delivery of

EMI components, as previously employed in other EMIs [32, 39-41]. The enhancing delivery of EMI components introduces participants to new EMI components during the introductory phase. The consolidating delivery allows participants to practice previously learned components at user-defined times, both during the introductory phase and the training phase. During the training phase, consolidating delivery of EMI components at user-defined times as well as interactive/adaptive delivery of EMI components at random times was provided with repeated randomization with equal probability to either the experimental condition, where EMI components were assigned using a ML-algorithm-based on EMA ratings of affect and behavior, or the active control condition, where EMI components were randomly assigned [31, 36]. Participants were repeatedly randomized to one of these two conditions up to seven times daily (once for consolidating delivery and six times for interactive/adaptive delivery), resulting in a maximum of 210 decision points. The type of assignment was recorded (ie, random, ML-based, or erroneous), with erroneous occurring in cases where, for example, a technical issue prevented the mobile connection to the server, making an ML-based assignment impossible. The current study only focused on the effect of initiation of EMI components independently from ML-based assignment of EMI components (and, hence, controlled for randomization to ML-based assignment of EMI components or random assignment of EMI components in all analyses). As in line with the Multiphase Optimization Strategy [42], the EMI and ML-algorithm was optimized after each of the three MRTs, we controlled for the MRT that the participant was assigned to.

There were at least 45 min (in MRT 1) or 90 min (in MRT 2 and MRT 3) between two EMA prompts and, thus, the subsequent assignment of interactive/adaptive EMI components. These components could be postponed by the participants by up to 20 min (in MRT 1) or up to 300 min (in MRT 2 and MRT 3). Participants were able to start the EMI component within 50 sec after it was suggested. When participants did not start the suggested EMI component, they were reminded to do so by an alarm up to 5 times (in MRT 1) or 3 times (in MRT 2 and MRT 3). The consolidating delivery of EMI components occurred twice per day during the introductory phase and once per day during the training phase at a user-defined time and could be postponed up to 65 min (in MRT 1) or 600 min (in MRT 2 and MRT 3). In MRT 2 and MRT 3, participants were able to request ML-based assignment of consolidating delivery of EMI components at any time during the day by button press.

Measures

Sociodemographic data and baseline characteristics were collected including age (in years), gender (male, female, diverse/not specified), migration history, and psychological distress at baseline measured using the Kessler Psychological Distress Scale [K10; 43].

During the training phase, EMA included six assessments per day, scheduled at random within set blocks of time at user-defined time periods. Participants received a signal (sound and/or vibration) to complete the EMA. For this analysis, an EMA was considered completed when participants completed the items measuring

positive affect, negative affect, stress, and resilience. Momentary positive affect was measured with the following three items: “I feel good”, “I feel relaxed”, “I feel satisfied”. For momentary negative affect, the three items “I feel scared”, “I feel down”, and “I feel sad” were rated. The mean of the respective items was calculated for positive affect and negative affect, respectively. If any items were missing, the mean was considered missing. Momentary stress was measured using the single item “I feel stressed” and momentary resilience was measured with the single item “I can handle all the difficulties that I may encounter”. All items were rated on a 7-point Likert scale ranging from not at all (rating of 1) to very much (rating of 7).

Statistical analysis

For all analysis, R (version 4.5.1) was used. To fit linear mixed-effects models, the packages *lme4* and *nlme* were used. For all analyses, the available data were included, and no imputation methods were applied to account for missing data. The required sample size for this secondary analysis was determined based on a study which showed that, in order to detect a mediation effect with a small effect size (ie, an indirect effect explains at least 4% of the total variance in the outcome variable), the required number of clusters is at least $n=100$ with cluster sizes ranging from 80 to 160 (with power=80% and $p<0.05$) [44]. To detect a medium effect (ie, Cohen’s $d=0.5$), only $n=50$ clusters would be required (with power=80% and $p<0.05$). In this study, the target size was 180 clusters (ie, participants) with cluster sizes up to 210.

All level-1 predictor variables (ie, positive affect, negative affect, stress, resilience) were centered using person-mean centering and z-standardized. Lagged variables for positive affect, negative affect, and stress were calculated for each time point an EMA was completed, using data from the most recently completed EMA prior to that time point within the same day.

To test the first hypothesis, linear mixed-effects models using restricted maximum likelihood estimation were used to account for the nested structure of EMA data (ie, time points nested within participants). Each model was controlled for age, gender, type of assignment of EMI components, and assigned MRT. For the first hypothesis, three separate models were fitted, with the outcome variable well-being at t_n being operationalized as i) positive affect, ii) negative affect and iii) stress, respectively. The independent variable was the dichotomous variable of whether an EMI component was initiated or not at t_{n-1} . It was controlled for i) positive affect at t_{n-1} , ii) negative affect at t_{n-1} or iii) stress at t_{n-1} . Random intercepts for individuals were assumed for i) positive affect at t_{n-1} , ii) negative affect at t_{n-1} and iii) stress at t_{n-1} to allow for inter-individual differences in the level of well-being. Random slopes for the effects of well-being at t_{n-1} and initiation of an EMI component at t_{n-1} were initially assumed, but the models were revised to exclude the random slope for well-being at t_{n-1} due to convergence issues.

For the second hypothesis, a moderator variable was added to the model. The moderator was the lagged well-being variable i) positive affect at t_{n-1} , ii) negative affect at t_{n-1} , or iii) stress at t_{n-1} . It was included in the model as a two-way interaction term with the dichotomous variable indicating whether an EMI component was

initiated at t_{n-1} . Linear contrasts were employed to examine any moderation effect. Random intercepts for the individuals were assumed for i) positive affect at t_{n-1} , ii) negative affect at t_{n-1} and iii) stress at t_{n-1} to allow for inter-individual differences in the level of well-being. In addition, random slopes for the effects of well-being at t_{n-1} and initiation of an EMI component at t_{n-1} , and the interaction of well-being at t_{n-1} and initiation of an EMI component at t_{n-1} were initially assumed, but due to convergence issues, the models were revised including only random slopes for initiation of an EMI component at t_{n-1} .

For the third hypothesis, three mediation models were fitted with difference scores ($t_n - t_{n-1}$) for the well-being variables i) positive affect, ii) negative affect, and iii) stress as the outcome variables and the difference score ($t_n - t_{n-1}$) for resilience as the mediator. To examine the mediation effects, a two-step multilevel modelling approach was used: First, a linear mixed-effects model was fitted to predict the mediator (ie, the change in resilience) depending on whether an EMI component was initiated at t_{n-1} . Second, a linear mixed-effects model was fitted to predict the outcome (ie, the change in well-being) depending on the initiation of an EMI component at t_{n-1} and the difference score for resilience. The initial model specification included random slopes for both the mediator and the outcome model. However, the models did not converge properly, and parameter estimates suggested that the random slopes did not explain meaningful variability. To ensure model stability and interpretability, the model was specified including only random intercepts for the individuals. To test the mediation effect of the change in resilience on the relationship between initiation of an EMI component and the change in well-being, the function “mediate” from the R package “mediation” was used. The mediation effect was evaluated using 1,000 bootstrap simulations to estimate indirect, direct, and total effects, along with their statistical significance.

RESULTS

Sample Characteristics

Of the 408 individuals identified for potential participation, 237 could be screened for eligibility. Of those, 190 individuals met the inclusion criteria and provided written informed consent. Thereafter, 11 participants discontinued their study participation before starting the AI4U training and 8 participants did not continue with the training phase after the 10-day introductory phase. In addition, 1 participant completed less than two EMA prompts within any day, and their data thus was not included to the analyses. Therefore, the analytic sample for this analysis comprised 170 individuals (ie, 56 in MRT 1, 56 in MRT 2, and 58 in MRT 3), who were mostly female (74.1%), with a mean age of 20.41 years. Characteristics of the full sample and the analytic sample can be found Table 1.

In total, participants completed 13059 EMA prompts and, in response to 6667 (51.1%) completed EMA prompts, interactive/adaptive EMI components were initiated within 45-min after the EMA was completed.

The frequency distribution for initiating EMI components was broadly similar across the eight different EMI components (see Supplementary Table 1). Aggregated means, skewness and kurtosis of the proximal outcome variables are shown in Table 1.

Table 1. Sample characteristics and descriptive statistics of proximal outcomes.

Sample characteristics			
Characteristic	Full sample (n=179)	Analytic sample (n=170)	
Gender, n (%)			
Female	128 (71.5%)	125 (73.5%)	
Male	44 (24.6%)	39 (22.9%)	
Diverse / not specified	3 (1.7%)	3 (5.3%)	
Missing	4 (2.2%)	3 (5.3%)	
Age, mean (SD)	20.36 (3.39)	20.4 (3.40)	
Migration history, n (%)			
No migration history	88 (49.2%)	83 (48.8%)	
Foreign born	10 (5.6%)	9 (5.3%)	
First generation migrant	48 (26.8%)	46 (27.1%)	
Second generation migrant	25 (14.0%)	24 (14.1%)	
Psychological distress at baseline, n (%)^a			
None	58 (27.9%)	49 (28.8%)	
Mild	60 (33.5%)	58 (34.1%)	
Moderate	37 (20.7%)	34 (20.0%)	
Severe	25 (14.0%)	23 (13.5%)	
Descriptive statistics of proximal outcomes assessed by EMA^b			
Positive affect			
Mean (SD)		4.64 (1.17)	
Skewness		-0.47	
Kurtosis		0.12	
Negative affect			
Mean (SD)		2.22 (1.20)	
Skewness		1.28	
Kurtosis		1.43	
Stress			
Mean (SD)		3.05 (1.66)	
Skewness		0.82	
Kurtosis		-0.13	
Resilience			
Mean (SD)		4.72 (1.35)	
Skewness		-0.52	
Kurtosis		0.03	

^aCut-offs to categorize psychological distress measured with K10: 'none' (range score: 10 to 19); 'mild' (range score: 20-24); 'moderate' (range score: 25-29); 'severe' (range score: 30-50).

^bAll EMA items have been completed on a 7-point scale (1= not at all, 7= very much). All values represent aggregated values over the 30-day training phase.

Initiation of an EMI Component at t_{n-1} and Well-Being at t_n

To examine whether well-being differed at t_n depending on whether or not an EMI component was initiated after the previous EMA prompt, linear mixed-effects models were specified for each of the three proximal outcome variables (ie, positive affect, negative affect and stress). All outcomes at t_{n-1} were associated with the respective outcome at t_n (Table 2). Findings did not signal a difference in positive affect at t_n ($b=0.00$, 95% CI -0.04 to 0.04, $d=0.00$), negative affect at t_n ($b=-0.01$, 95% CI -0.05 to 0.03, $d=-0.01$), or stress at t_n ($b=0.01$, 95% CI -0.03 to 0.05, $d=0.01$) for initiating an EMI component at t_{n-1} vs. not initiating an EMI component at t_{n-1} , as zero was included in the confidence interval. None of the potential confounding variables were associated to a relevant extent with the proximal outcomes. Sensitivity analyses showed that the results remained largely unchanged when analyzing the effect of initiating a specific type of EMI component vs. not initiating any EMI component (Supplementary Table 4). The reason why an EMI component was not initiated (ie, because none was suggested by the app vs. because the participant did not initiate the suggested component) did also not alter the results (Supplementary Table 9).

Table 2. Effects of initiating an EMI component at t_{n-1} on well-being at t_n ^a.

Outcome: Positive affect at t_n				
	b	95% CI	P	d
Initiation of EMI component at t_{n-1}	0.00	-0.04 - 0.04	.97	0.00
Positive affect at t_{n-1}	0.45	0.43 - 0.46	<.001	0.50
Outcome: Negative affect at t_n				
	b	95% CI	P	d
Initiation of EMI component at t_{n-1}	-0.01	-0.05 - 0.03	.53	-0.01
Negative affect at t_{n-1}	0.37	0.35 - 0.38	<.001	0.41
Outcome: Stress at t_n				
	b	95% CI	p	d
Initiation of EMI component t_{n-1}	0.01	-0.03 - 0.05	.65	0.01
Stress at t_{n-1}	0.39	0.37 - 0.41	<.001	0.42

^aAdjusted for potential confounding by age, gender, assignment of EMI component, and MRT

Effects of Initiating an EMI Component at t_{n-1} and Well-Being at t_n by Well-Being at t_{n-1}

Linear mixed-effects models were used to examine whether the magnitude of the effect of initiating an EMI component at t_{n-1} vs. not initiating an EMI component at t_{n-1} on well-being at t_n differed depending on the level of well-being at t_{n-1} (Table 3). There was no strong difference in the magnitude of effect of initiating an EMI component vs. not initiating an EMI component at t_{n-1} on positive affect at t_n when positive affect at t_{n-1} was high vs. low ($b=0.07$, 95% CI=-0.00 to 0.15, $d=0.08$), with the effect size falling just short of being small. Also, findings signaled trivial effect sizes for the difference in positive affect at t_n for initiating vs. not initiating an EMI component at t_{n-1} .

when positive affect at t_{n-1} was high ($d=0.04$) and low ($d=-0.04$). Similarly, the effect size for magnitude of effect of initiating an EMI component vs. not initiating an EMI component at t_{n-1} on stress at t_n when stress at t_{n-1} was high vs. low fell just short of being small ($b=0.07$, 95% CI=-0.01 - 0.15, $d=0.08$). Findings signaled trivial effect sizes for the difference in stress at t_n for initiating vs. not initiating an EMI component at t_{n-1} when stress at t_{n-1} was high ($d=0.05$) and low ($d=-0.03$). There was no difference in the magnitude of effect of initiating an EMI component vs. not initiating an EMI component at t_{n-1} on negative affect at t_n when negative affect at t_{n-1} was high vs. low ($b=-0.01$, 95% CI=-0.09 to 0.06), as signaled by a trivial effect size ($d=-0.01$). All outcome variables at t_{n-1} were associated with the respective outcome variables at t_n (Table 3). Sensitivity analyses revealed that the results remained broadly similar when considering the type of EMI component (Supplementary Table 4) and the reason for non-initiation of an EMI component into account (Supplementary Table 10).

Table 3. Effects of initiating an EMI component at t_{n-1} and well-being at t_n by well-being at t_{n-1} ^a.

Outcome: Positive affect at t_n					
	b	95% CI	P	d	
Initiation of EMI component at t_{n-1}	0.00	-0.04 - 0.04	.94	0.00	
Positive affect at t_{n-1}	0.43	0.4 - 0.45	<.001	0.48	
Initiation of EMI component at t_{n-1} × Positive affect at t_{n-1}	0.04	-0.00 - 0.07	.07	0.04	
High positive affect	0.04	-0.03 - 0.10	.35	0.04	
Low positive affect	-0.03	-0.10 - 0.03	.40	-0.04	
High vs. low pos. affect	0.07	-0.00 - 0.15	.07	0.08	
Outcome: Negative affect at t_n					
	b	95% CI	P	d	
Initiation of EMI component	-0.01	-0.05 - 0.03	.53	-0.01	
Negative affect at t_{n-1}	0.37	0.34 - 0.40	<.001	0.41	
Initiation of EMI component at t_{n-1} × Negative affect at t_{n-1}	-0.01	-0.05 - 0.03	.74	-0.01	
High negative affect	-0.02	-0.08 - 0.05	.77	-0.02	

Low negative affect	-0.01	-0.07	- .98	-0.01
		0.06		
High vs. low neg. affect	-0.01	-0.09	- .74	-0.01
		0.06		
Outcome: Stress at t_n				
	<i>b</i>	95% CI	<i>P</i>	<i>d</i>
Initiation of EMI component t_{n-1}	0.01	-0.03	- .68	0.01
		0.05		
Stress at t_{n-1}	0.37	0.34	- <.001	0.41
		0.40		
Initiation of EMI component at t_{n-1} × Stress at t_{n-1}	0.04	-0.00	- .07	0.04
		0.08		
High stress	0.04	-0.02	- .24	0.05
		0.11		
Low stress	-0.03	-0.09	- .58	-0.03
		0.04		
High vs. low stress	0.07	-0.01	- .07	0.08
		0.15		

^aAdjusted for potential confounding by age, gender, assignment of EMI component, and MRT

Effects of Initiating an EMI Component at t_{n-1} on Changes in Well-Being From t_{n-1} to t_n via Changes in Resilience From t_{n-1} to t_n

Three mediation analyses were conducted to examine the effects of initiation of an EMI component on changes in proximal well-being outcomes from t_{n-1} to t_n via changes in momentary resilience from t_{n-1} to t_n as a potential mediator while controlling for well-being at t_{n-1} . The results of the linear mixed models for the mediator indicated that there was no difference in change in resilience from t_{n-1} to t_n for initiating an EMI component at t_{n-1} vs. not initiating an EMI component at t_{n-1} (Supplementary Table 2). Change in resilience was associated with changes in well-being in all three models (Supplementary Table 3): Change in resilience predicted change in positive affect ($b=0.22$, 95% CI 0.21 to 0.24, $d=0.26$), indicating that a greater increase in resilience was associated with a greater increase in positive affect. Similarly, change in resilience predicted change in negative affect ($b=-0.14$, 95% CI -0.16 to -0.13, $d=-0.16$) suggesting that a greater increase in resilience was associated with a greater decrease in negative affect. Change in resilience was also a predictor of change in stress ($b=-0.15$, 95% CI -0.17 to -0.13, $d=-0.14$), indicating that an increase in resilience was associated with a decrease in stress. In all three models, the effect of initiating an EMI component on changes in proximal well-being outcomes was not mediated via changes in resilience (Table 4).

Findings were broadly similar in sensitivity analyses taking into account the specific type of EMI component (Supplementary Tables 6-8) and the reason for not initiating an EMI component (Supplementary Tables 11-13).

Table 4. Effects of initiating an EMI component at t_{n-1} on change in well-being from t_{n-1} to t_n via change in resilience from t_{n-1} to t_n (mediation model)^a.

Outcome: Change in positive affect			
	<i>b</i>	95% CI	<i>P</i>
Total effect	0.00	-0.04 - 0.04	.92
Direct effect	0.00	-0.04 - 0.03	.83
Indirect effect	0.01	0.00 - 0.02	.31
Proportion mediated	0.12	-5.08 - 5.39	.85
Outcome: Change in negative affect			
	<i>b</i>	95% CI	<i>P</i>
Total effect	-0.01	-0.05 - 0.03	.44
Direct effect	-0.01	-0.05 - 0.03	.53
Indirect effect	0.00	-0.01 - 0.00	.38
Proportion mediated	0.12	-2.16 - 3.23	.56
Outcome: Change in stress			
	<i>b</i>	95% CI	<i>P</i>
Total effect	0.01	-0.03 - 0.05	0.53
Direct effect	0.01	-0.03 - 0.05	0.53
Indirect effect	0.00	0.00 - 0.00	>.999
Proportion mediated	0.00	0.00 - 0.00	>.999

^aAdjusted for potential confounding by age, gender, assignment of EMI component, and MRT

DISCUSSION

Principal Findings

This secondary analysis of data collected in the AI4U project sought to explore proximal effects of a compassion-focused smartphone-based digital training for youth on momentary outcomes of well-being (ie, positive affect, negative affect, stress). We did not find convincing evidence that well-being at a time point differs depending on whether an EMI component was initiated at the previous time point vs. when no EMI component was initiated. There was also no strong indication that this potential effect may be influenced by well-being at the time of EMI initiation. While changes in resilience predicted changes in well-being, the results did not suggest that changes in resilience were linked to prior initiation of an EMI component, and that changes in resilience mediated the relationship between EMI initiation and changes in well-being.

Methodological Considerations

When interpreting the reported results, it is important to consider that all analyses were performed as secondary analyses and that the original study [31] was neither designed nor powered to test the hypotheses of this paper. Sample size considerations for these secondary analyses were based on a previous simulation study [44], which indicates that the available sample size may be sufficient for these secondary analyses. However, it is possible that the sample size was still not large enough to detect effects of EMI component initiation, taking into account that each of the three MRTs was primarily powered to detect one proximal effect of ML-based EMI delivery and not for additional tests performed as part of current exploratory analyses. In addition, the following five methodological aspects need to be considered.

First, in order to explore proximal effects of EMI components in the current analysis, completed EMA prompts before (t_{n-1}) and after (t_n) EMI components that were initiated were considered. The time interval between an EMI and the next completed EMA prompt was not fixed and depended on the compliance of participants. Thus, it may be the case that participants missed or ignored EMA prompts after initiation of the EMI. The subsequent EMA was therefore not necessarily in a close temporal relationship with the preceding EMI component. In the time interval between an EMI component and the following EMA, proximal effects may have attenuated and/or external influences may have occurred with a potentially larger effect on affect and stress than the EMI component. While the current approach allowed for some approximation to proximal effects of EMI components, a change in affect or stress from t_{n-1} to t_n does not depict the actual proximal effect of EMI components, as in some cases, several hours could have passed between initiating the EMI component and completing the next EMA prompt. Thus, future studies on proximal effects of EMI components should implement an EMA directly after each EMI component (ie, within minutes).

Second, due to the nature of EMA and EMI, participants completed both the assessments and the interventions in their daily life, that is, without supervision. Therefore, it remains unknown whether an EMI component that was initiated was indeed completed in accordance with the instructions or participants were distracted by, or occupied with other tasks. Qualitative data shows that several participants found it challenging to complete EMA and EMI when not at home but for example in public and that they were sometimes not completed conscientiously [37]. Likewise, participants were provided with the option to perform EMI exercises that they found helpful on their own (as part of consolidating delivery of EMI components), that is, when no EMI component was suggested by the app. It is also possible that participants performed exercises they learned during the AI4U training independently, as several participants reported that they integrated the breathing intervention

in their everyday lives even beyond the duration of the study [37]. This may have masked potential effects of the EMI component and thus bias our findings. Asking participants, for example, as part of the EMA for collecting proximal outcome data or at the end of the EMI training phase to which degree they complied with the training instructions or implemented EMI exercises into their everyday lives independent of being prompted may provide more insight into EMI adherence, engagement and fidelity.

Third, this analysis focused on effects of EMI components that were initiated after EMA completion upon suggestion (ie, interactive/adaptive EMI), which allowed to approximate a quasi-experimental 'within-subject control condition' (ie, occasions where an EMI component was suggested vs. occasions when no EMI component was suggested). However, the sampling scheme was more complex including consolidating delivery of EMI components on demand and at pre-scheduled times based on self-set reminders. Especially self-initiated EMI components are very likely to be completed according to instructions, with high fidelity, when deemed helpful by participants. Therefore, especially self-initiated EMI components may have a more marked effect on mental well-being. Future investigations should therefore consider all initiated EMI components in investigating proximal EMI effects, including self-initiated EMI components.

Fourth, the EMI components differed in their content and not all EMI components were designed and expected to generate immediate effects. For example, the "compass of emotions" component served predominantly psychoeducational purposes that are unlikely to have a proximal effect. When looking at each of the types of EMI components separately, sensitivity analysis did not detect effects of the type of EMI that was initiated. This contrasts the findings of other authors [30], who found evidence for initial signals that the effect of completing a compassion-focused EMI component (vs. not completing an EMI component) was more pronounced when the type of EMI component was either 'breathing exercise' or 'soothing imagery' (comparable to 'positive imagery' in this study). It may therefore be valuable to further investigate the effects of different EMI types.

Fifth, to keep burden as low as possible for participants, while still ensuring that all relevant aspects were assessed, proximal outcomes were assessed with only one to three items. However, this may result in only a limited aspect of the broader constructs of affect, stress, and resilience to be captured. Especially resilience, which is assessed in this study using only a single item, is thought to be actually a very complex and dynamic process comprising various resilience factors [45, 46]. The item used in this study, "I can handle all the difficulties that I may encounter", was intended to

capture capacity to withstand or recover quickly from difficulties, as a core aspect of resilience [45], but it neglects other important aspects such as perceived social support and sense of coherence [47, 48]. A more comprehensive EMA measure of resilience may facilitate the detection of changes in these specific aspects, but needs to be carefully considered in the light of the additional burden on the participants.

Comparison to Prior Research

There is growing evidence on the effectiveness of EMI for various outcomes related to mental health [24, 25, 49]. However, many previous studies and also the primary analysis of the current study [31] focused on distal outcomes in promoting mental health and well-being. While evidence on these outcomes is important, they are more limited in how exactly specific EMI components exert their effects over time. Our study extended previous research by investigating proximal effects of EMI and thereby addressing the theoretical assumption [19], and building on prior evidence, that EMIs have an effect at the momentary level [20, 21, 50]. However, so far, there is limited evidence on proximal effects of EMIs on mental health related outcomes. In one study, an EMI was used to promote CBT skills practice in patients admitted for suicidal ideation or behavior during and after their inpatient stay [51]. When an EMA measuring negative affect was followed by an EMI to engage in CBT skills practice, negative affect measured directly after the skills practice improved compared to when no EMI was prompted. While the sample was small ($n=25$) and drawn from a specific clinical population, the results highlight that immediate effects of an EMI can be detected using EMA. Nevertheless, the authors emphasized that as the study lacked a control group, it may be possible that the observed effects were not exclusively attributable to the EMI, but rather influenced by the multiple sessions conducted during the inpatient stay, in which participants learned CBT skills. In contrast to the study by Bernstein, Bentley [51], in our study, the subsequent EMA measuring positive and negative affect and stress did not differ depending on whether a single EMI component was initiated vs. not initiated at the previous time point. However, different to Bernstein, Bentley [51], in our study, the next EMA did not immediately follow the EMI component. In addition, our sample consisted of young individuals, who were not necessarily in contact with mental health services, and without a current diagnosis of a mental health condition. The EMI implemented in this study did accordingly not serve as a therapeutic intervention but an intervention for mental health promotion and prevention. Hence, our sample also is likely to have experienced a lower intensity or less fluctuations of negative affective states. This assumption is supported by the distribution of ratings of EMA items (Table 1), which for all proximal outcome variables is skewed towards ratings

indicating high well-being (ie, low stress, low negative affect, high positive affect), indicating potential floor and ceiling effects. In a different study, an EMI for smoking cessation was found to have proximal effects on negative affect at the next time-point as well as after completion of one week of the training [27]. However, the effect of the EMI could not be observed on other outcome variables (eg, positive affect). Therefore, while the study used a different intervention and focused on a different population [27], the results align, to some extent, with the results of the current study. In the primary analysis of this study, using data of the first of three MRT, the authors found that when EMI components were allocated ML-based, levels of momentary resilience at the next time point were on average higher compared to when EMI components were allocated at random [31]. In addition, they found evidence for uncontrolled effects of the EMI on distal outcomes, that is, an increase in resilience and the use of adaptive emotion regulation strategies and a decrease in psychological distress. Furthermore, qualitative analyses of the AI4U training indicate that the participants' subjective mental well-being did improve during the AI4U training as several participants reported improvements in their emotion regulation and self-reflection on emotions [37].

Echoing previous research [6, 7], our results showed that resilience was associated with indicators of well-being. This highlights the role resilience may play for mental well-being. Previous research on the relationship between resilience and well-being has primarily relied on cross-sectional assessments or aggregated EMA data. To our knowledge, only a limited number of studies [20] have so far investigated the association between changes in momentary resilience, on the one hand, and changes in momentary affect and stress, on the other. Our results showed that an increase in resilience from one EMA to the next was associated with an increase in positive affect and a decrease in negative effect and stress. This indicates that the widely reported association of resilience and well-being can also be found at the momentary level. Momentary resilience was, however, not affected by initiation of an EMI component at the previous time point. One possible explanation for this may be that, for digital interventions to be effective, it is necessary that participants engage with them [52, 53]. The high variability in and mean of the number of days of training in this sample (Table 1) may indicate that, while many participants strongly engaged with the training, some engaged only to a limited extent. According to qualitative feedback of participants, possible reasons for low engagement could be feeling uncomfortable using the AI4U training in public or experiencing the repeated prompts as distracting [37]. As low compliance reduces exposure to EMI components over time, it may attenuate its potential impact: Without sufficient interaction with the EMI, the mechanisms leading to an increase in resilience and well-being may not be active to a detectable degree. Thus, the lack of proximal effects of EMI initiation on the next EMA may not

necessarily indicate that there is no proximal effect of the EMI, but may rather be due to low adherence to the EMI. Identifying factors associated with low adherence should be the focus of further research.

Another explanation for our findings may be that the completion of EMA prompts may have per se an effect on well-being and, hence, reflected an active ‘within-subject control condition’ non-inferior to proximal effects of EMI components. Prior research has shown that smartphone-based self-monitoring of emotions can have a positive effect on mental health even without the implementation of an EMI [54, 55]. The potential mechanism behind this effect may be that emotional self-awareness may increase as a result of repeated self-monitoring [54], which, in turn, may positively impact on mental health. It is tempting to speculate whether the EMA delivered as part of the AI4U training may have had an effect on well-being that obscured the effect of the EMI. However, the design of the current study does not allow for disentangling this potential masking effect, which highlights the importance of future methodological work on how EMI operate and exert their beneficial effects.

Implications

This secondary analysis did not support the hypothesis that momentary mental well-being (ie, positive affect, negative affect, stress) at a time point differed depending on whether or not an EMI component was initiated at the previous time point during a 30-day EMI training for mental health promotion in youths. However, an increase in momentary resilience was associated with an increase in momentary well-being. This finding supports targeting momentary resilience (and its influential factors) by EMI as a promising strategy for promoting mental health and well-being in youth.

Future work should consider several aspects that are relevant for disentangling beneficial proximal and distal effects of EMIs, as reported by prior research [31]. This includes the implementation of more comprehensive instruments to assess proximal outcomes in closer temporal proximity to the previous EMI component. In addition, compliance to the EMI needs to be explored, as proximal effects of EMI may only be detectable when at a minimum level of compliance. This would allow us to further extend our knowledge on proximal effects of EMI and to understand which factors are relevant for EMI to be effective in supporting mental well-being. By exploring ways to promote facilitating factors such as compliance, we will understand more fully the proximal effects of EMI and how they unfold to translate into previously reported beneficial effects on distal outcomes.

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Conflicts of Interest

None declared.

Data Availability

The datasets generated or analyzed during this study are not publicly available due to reasons of data protection but are available from the corresponding author on reasonable request.

Authors' Contributions

Conceptualization: UR, SK, DD, GK, CR, JF, SH, CG, AS, EW

Data curation: JF, GK, CR, EW

Formal analysis: EW (lead), AS (supporting)

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Investigation: CR, EW

Supervision: UR, AS

Writing – original draft: EW

Writing – review & editing: UR, SK, DD, GK, CR, JF, SH, CG, AS, EW

Abbreviations

CBT – cognitive behavioral therapy

EMA – ecological momentary assessment

EMI – ecological momentary intervention

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