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4 **Spacing, feedback, and testing boost vocabulary learning in a web application**

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Abstract

Information and communication technology (ICT) becomes more prevalent in education but its general efficacy and that of specific learning applications are not fully established yet. One way to further improve learning applications could be to use insights from fundamental memory research. We here assess whether four established learning principles (spacing, corrective feedback, testing, and multimodality) can be translated into an applied ICT context to facilitate vocabulary learning in a self-developed web application. Effects on the amount of newly learned vocabulary were assessed in a mixed factorial design ($3 \times 2 \times 2 \times 2$) with the independent variables Spacing (between-subjects; one, two, or four sessions), Feedback (within-subjects; with or without), Testing (within-subjects, 70% or 30% retrieval trials), and Multimodality (within-subjects; unimodal or multimodal). Data from 79 participants revealed significant main effects for Spacing ($F[2, 76] = 8.51, p = 0.0005, \eta_p^2 = 0.18$) and Feedback ($F[1, 76] = 21.38, p < 0.001, \eta_p^2 = 0.22$), and a significant interaction between Feedback and Testing ($F[1, 76] = 14.12, p = 0.0003, \eta_p^2 = 0.16$). Optimal Spacing and the presence of corrective Feedback in combination with Testing together boost learning by 29% as compared to non-optimal realizations (massed learning, testing with lack of corrective feedback). Our findings indicate that established learning principles derived from basic memory research can successfully be implemented in web applications to optimize vocabulary learning.

Keywords: distance education, distance learning, online learning, web application, memory, language learning, vocabulary learning

Introduction

Information and communication technology (ICT) changes how we access information and the way we learn. Smartphones, tablets, and desktop-computers become ubiquitous in living rooms and classrooms, transforming how learners of all ages perceive and interact with learning material. Identifying how ICT may improve learning is vital to ensure successful adaptation of educational practices for the digital age (Sung et al., 2016). In the current work, we investigate this general question by addressing the following specific research gaps: 1) Can some of the best researched learning principles originating from basic memory research be applied to optimize computer-assisted learning environments? 2) How do these learning principles interact? We do that in the setting of vocabulary learning because it is a central task in classes of foreign languages in schools. Vocabulary learning lends itself well to assess these questions because the transfer between basic memory research and its application seems rather close: Vocabulary learning essentially entails long-term storage of memories for paired-associates (i.e., a word and its associated translation in the foreign language), a well-researched phenomenon in basic memory research (Steinel et al., 2007).

A meta-meta-analysis in 2011 summarized 25 meta-analyses and found a small to moderate effect favoring the use of computer technology in the classroom to support teaching and learning, but also great variability among the results (Tamim et al., 2011). The efficacy of interactive learning applications to improve learning in classrooms is similarly promising and unclear (Sung et al., 2016). Some meta-analyses report beneficial effects initially that fade after 6 to 12 months (Cheung & Slavin, 2013; Sung et al., 2016). This fading of effects might represent an initial motivation boost when ICT is first introduced. As plans to invest more resources for ICT in classrooms emerge (European Commission, 2019; Futuresource Consulting, 2016;

Roediger & Pyc, 2012), more research is needed that investigates not just whether but *how* ICT can be successfully applied in education. Such research could deepen our understanding of the variation of outcomes reported earlier and identify features of apps and learning situations contributing to successful implementations of ICT in education.

One approach to scrutinize underlying mechanisms of ICT success is to take the perspective of a researcher interested in fundamental memory processes. This perspective has surprisingly seldom influenced common educational practices in classrooms or learning applications (Reber & Rothen, 2018; Roediger & Pyc, 2012). A commentary recently proposed to focus on four established learning principles known to facilitate learning in laboratory situations which are also straightforward to implement in digital learning applications (Reber & Rothen, 2018).

Probably the most research-backed of the four principles is derived from the *spacing effect*. Spacing refers to splitting up the learning time into several short sessions and distributing them over time (Carpenter et al., 2012; Kornell et al., 2010). Learning is improved when we space out the learning time into separate distributed sessions, in contrast to cramming it into one session, also called massing (Benjamin & Tullis, 2010; Cepeda et al., 2006; Delaney et al., 2010).

A second principle concerns giving *corrective feedback* about mistakes in comparison to no feedback or simple right/wrong feedback (Metcalf, 2017). From a cognitive perspective, corrective feedback leads to a “prediction-error” signal in the brain (Wilkinson et al., 2014), which catalyzes learning by switching brain regions relevant for long-term memory into a more receptive encoding rather than retrieval mode (Greve et al., 2017; Lisman & Grace, 2005).

81 The third principle builds on the *testing effect* (also test-enhanced learning or retrieval
82 practice). When people have to reproduce or answer questions about the studied material, they
83 remember more than when they study it repeatedly (Rowland, 2014). Better performance due to
84 testing has been explained on one hand by the *transfer-appropriate processing framework*,
85 which posits that memory is better when learning and test situations are similar rather than
86 different (Morris et al., 1977). That is, being able to recall information is more likely when
87 recalling information was practiced in comparison to restudied. On the other hand, testing
88 situations afford more effort which may lead to deeper encoding of material according to the
89 *desired difficulties framework* (Bjork, 1994; Bjork & Kroll, 2015).

90 Finally, presenting the learning material *multimodally*, i.e. to multiple senses
91 simultaneously, benefits learning as well (Kast et al., 2007, 2011; Shams & Seitz, 2008).
92 Multimodal presentation is inarguably closer to how we perceive the world and learn every day,
93 without deliberate effort (incidental learning), than to present learning material for only one
94 sensory channel. Furthermore, e.g. audio-visual presentations of learning materials recruit larger
95 regions of the brain - namely the ones processing auditory and visual information - as compared
96 to unimodal presentations (auditory or visual stimuli alone). These “many routes” (Bjork, 1975)
97 by which a stimulus is processed for encoding are thought to facilitate retrieval by making use of
98 redundant information stored in distributed brain regions (Murray & Sperdin, 2010).

99 While extensive data on these four principles exist, few studies assessed how they
100 interact (Weinstein et al., 2018). A notable exception looked at the interaction between spacing
101 and testing: In a word pair learning task, testing improved learning success and this effect was
102 even higher when the learning time was spaced beyond mere addition of the main effects (Cull,
103 2000).

This is also interesting considering that popular language learning and general learning tools available online already implement some learning principles we investigated: Duolingo (www.duolingo.com), Rosetta Stone (www.rosettastone.com), Memrise (www.memrise.com), Anki (apps.ankiweb.net), and Quizlet (www.quizlet.com) for example all implement testing, feedback, and multimodality in some way or another. The flashcard-style learning applications Anki and Quizlet both further implement spacing based on the so-called Leitner system, an algorithm to space and prioritize flash-cards (Godwin-Jones, 2010). Duolingo applies a self-developed procedure for spaced repetition using Half-Life Regression (Settles & Meeder, 2016). Please note that what we mean in the context of this manuscript by “spacing” is slightly different from “spacing” in the Leitner system. We refer to spacing of individual learning sessions, whereas the mentioned spacing algorithms refer to the scheduling of individual learning items within and across individual learning sessions.

The above learning principles were mostly researched using traditional learning methods (no use of ICT) in laboratory or classroom settings. The purpose of this study is to investigate whether these principles also improve learning efficiency with a web application in a home environment. A further aim is to explore the interactions between these principles. Our main research question (RQ1) was: “Can established learning principles be used to optimize learning of vocabulary with a web application?” Consequently, our hypotheses were: Learning success, as measured in a cued recall test, is improved when: (a) the time spent learning is spaced vs. massed (H1), (b) corrective feedback is given vs. no feedback is given (H2), (c) more retrieval trials are presented for a specific word pair (H3), and (d) stimuli were presented multimodally vs. unimodally (H4). Our second research question (RQ2) was: “Are there any significant pairwise interactions between these principles?”. To approach these questions, we implemented a web

application that allows for independent variation of presence or absence and/or parametrization of all four learning principles. German-speaking participants used the app to learn Finnish language vocabulary and we tested their recall two days after their last learning session.

Material and Methods

Design

Our study was a $3 \times 2 \times 2 \times 2$ mixed factorial design with independent variables *Spacing* (between-subjects, one, two, and four learning sessions), *Feedback* (within-subjects, with and without corrective feedback), *Testing* (within-subjects, proportions of retrieval and learning trials were 70%/30% or 30%/70%), and *Multimodality* (within-subjects, unimodal [visual only] and multimodal [audio-visual]). The dependent variable was the proportion of correct translations recalled in the testing session. Additionally, we varied the independent variable *learning direction* (within-subjects) in the learning phase, and *testing direction* (within-subjects) in the test phase.

Participants

Participants were recruited among friends and acquaintances of the students in a class on experimental research in the bachelor's program in psychology, conducted at UniDistance Suisse in the autumn semester of 2018. Psychology students acted as experimenters ($N_e = 22$) and recruited $N_p = 87$ participants. Participants received no compensation, but a small thank-you gift was made by some of the experimenters. Participants gave written informed consent.

We analyzed data from 79 participants (43 female, 30 male, 6 undisclosed gender; age ranged between 16 and 77 years [$M = 39.7, SD = 15.5$]) after excluding 8 participants according to the following criteria: 3 had not completed the learning phase, 3 had not adhered to

the scheduled gaps between sessions required for proper operationalization of the spacing factor, 1 had a long gap (over 20 min) during the testing session, and for 1 participant age data was missing.

All participants were either native or advanced German speakers (73 natives, 4 near-native, 1 proficient, 1 advanced). None of the participants reported any previous knowledge of the Finnish language or any closely related language, such as Hungarian or Estonian.

Fourteen participants held a bachelor's degree, 21 a master's degree, 25 had finished an apprenticeship, 8 held a higher education entrance qualification, 5 had finished compulsory education, and 6 reported another form of education or were still in school.

Materials

Stimuli

We used 48 Finnish-German word pairs as stimuli, gathered from various lists of frequently used words in Finnish and English, lyrics of Finnish pop songs, and words from a Finnish online dictionary. We filtered an initial list of 250 words and removed Finnish words that seemed too similar to a German word, ambiguous terms, compound words, interrogatives, personal pronouns, and terms that were subjectively too complicated or too simple. This resulted in 214 stimuli, out of which the final set of 48 word pairs was selected randomly. A list of all stimuli is available in the supporting materials online repository at <https://osf.io/djxmr>. Audio files for the stimuli were created with the text-to-speech software Balabolka (v. 2.14.0.676, Ilya Morozov).

Learning application

For the learning phase, we developed a web application written in the R programming language (R Core Team, 2018), and we used the “shiny” (Chang et al., 2018) and “ShinyPsych”

(Steiner et al., 2018) packages. We hosted the applications with the open source version of “Shiny Server” (v. 1.5.9.923, RStudio, Boston, MA, U.S.) on a virtual server running Linux Debian (v. 4.9.110). The participants could use the app by navigating to an URL linked to our server and start learning sessions using a personalized username and password. The app recorded all data on the webserver.

For the implementation of the between-subjects factor Spacing, we kept the overall learning time equal for all participants but split it into either (a) one learning session of 80 minutes, (b) two sessions of 40 minutes, or (c) four sessions of 20 minutes. The sessions were further split into 20-minute learning blocks. Thus, every participant conducted four 20-minute learning blocks altogether. The levels of the variable Spacing (1, 2, or 4 sessions) were equally distributed among the experimenters, but the participant allocation to the levels was not done entirely at random: The rigid scheduling of several sessions would have made it impossible for some to participate. Thus, the participants’ preferences were considered in regard to having two, three, or five sessions with the experimenter (1, 2, or 4 learning sessions plus one testing session). The participants did not know any specifics about the experiment or study procedure at the point on which the sessions were scheduled. The overall procedure was only explained to them after scheduling the sessions, during the first learning session.

The 48 word pairs were assigned to the 16 factor-combinations of the three main within factors (Feedback, Testing, Multimodality) and learning direction. This assignment was randomized for each participant but was fixed during the whole learning phase of the participant.

Testing varied in the proportion of *learning* vs. *retrieval* trials. *Learning trials* entailed the presentation of a word pair in both languages and *retrieval trials* entailed presentation of one word as cue (German or Finnish) and an input field in which participants were prompted to input

the translation of the word (see Fig 1). Each trial was either a learning or retrieval trial. Among all trials of one word pair, the proportion of retrieval trials and learning trials was set to either “70% retrieval trials and 30% learning trials” or “30% retrieval trials and 70% learning trials”.

Fig 1. Screenshots of Learning and Retrieval Trials in the Web App

Note. Screenshots showing examples of learning trials (A) and retrieval trials (B) as they were displayed to participants in the web applications. Translation for German terms: “Weiter” = “continue”.

Corrective feedback was provided for some translations but not for others and entailed showing the correct solution along with the cue word and the answer given by the participant, after an incorrect answer to a retrieval trial. If the answer was correct, feedback entailed the presentation of the word “correct” and the participant could proceed to the next trial (see Fig 2).

Fig 2. Screenshots of Feedback Display in the Web App. Screenshots showing feedback screens as they were displayed to participants in the learning application. On the left side is an example of the feedback for correct answers and on the right side is an example of corrective feedback in case of a wrong response, which also shows the complete word pair and the wrong answer the participant gave. Translation for German terms: “Falsch” = “Wrong”, “Richtig” = “correct”, “Die Lösung ist” = “the solution is”, “Ihre Antwort war” = “your answer was”, “Weiter” = “continue”.

Multimodality entailed trials with multimodal vs. unimodal presentation. For multimodal (audio-visual) stimulus presentation, a word was displayed in either German or Finnish while an audio file of the word spoken by a computer voice was played simultaneously in the same language. In learning trials, the audio recording was played only for the word displayed on top of

the screen, not for the translation in the other language shown below. In unimodal trials, no audio recording was played.

We controlled for potential effects of learning direction. A word pair could either be learned in the direction from L1 (German) to L2 (Finnish) or the other way around (*L2-to-L1*). In learning trials, the first word was at the top of the screen, and its translation was below. In retrieval trials, the first word was at the top, and the input field into which the participants could enter the translation was below.

Test application

The test application was used during the final testing session and displayed only retrieval trials. We varied the independent variable *testing direction*: Each of the 48 word pairs was tested once in either direction (L1-to-L2 and L2-to-L1), resulting in 96 trials. Participants received no feedback on individual trials.

Questionnaires

We assessed sociodemographic information and motivation with a questionnaire created in LimeSurvey (v. 3.14.3+180809, LimeSurvey GmbH, Hamburg, Germany. Motivation was measured with the Questionnaire on Current Motivation (QCM) in its German version “Fragebogen zur Erfassung aktueller Motivation in Lern- und Leistungssituationen” (Rheinberg et al., 2001).

Procedure

For each learning and testing session, one experimenter met individually with one participant at a time. Experimenters followed a written guideline (available in the supporting materials online repository at <https://osf.io/djxmr>). The experiment was either conducted at the experimenter’s or the participant’s home and participants could use their own computer or one

provided by the experimenter. There was an exception for four experimenters (and thus 16 participants), who tested their participants without being physically present. Instead, they kept contact with the participants via video call on an additional device during the experiment. Whether participants were tested remotely or not had no effect on the conclusions of the experiment, as analyses excluding these participants were virtually identical to the main analyses presented in the Results section (Table S1).

The experiment started with the online questionnaire. Next, the participants began learning with the web application in their first study session. The first screen contained information on how to interact with the application and a query to check the audio settings.

Depending on the level of Spacing, the participants performed multiple 20-minute blocks in the same learning session and could take short breaks in-between (about 5-10 minutes). Within each 20-minute block, there were three phases of equal duration during which a set of 16 word pairs was learned, one word for each of the 8 within-subject factor-combinations, in both learning directions. The three sets were presented in the same order in all 20-minute blocks.

For each trial, a word pair was randomly chosen from the active set of 16 word pairs. If the word pair was chosen for the first time, it was presented as learning trial; otherwise, it was presented as learning or retrieval trial with a probability according to the Testing condition. Learning trials proceeded by button press or mouse click; retrieval trials by submitting a response via keyboard, followed by feedback depending on the condition.

Overall, all participants learned the same 48 word pairs and had a total learning time of 80 minutes. Due to randomized presentation of word pairs, the number of trials per word pair and participant varied ($M = 22.3, SD = 0.687$), but an analysis of variance (ANOVA) showed that

while there were slight differences in the number of trials between the factor conditions, those are unlikely to account for our results (see Tables S3 and S4).

Between learning sessions and between the last learning session and the testing session, a gap of two days was planned and the actual mean gap time ranged from 42.8 h to 77.2 h between subjects (Med = 69.7, IQR = 22.8). We will refer to the gap between individual learning sessions as *inter-study interval* (ISI) and to that between the last learning session and the testing session as *retention interval* (Cepeda et al., 2006). In the testing session, participants conducted a cued recall test of all learned translations using the testing application. The 96 trials were presented in randomized order.

Results

Learning Principles

To assess the effects of the four learning principles on recall, we conducted a four-way $3 \times 2 \times 2 \times 2$ mixed design ANOVA with factors Spacing (1, 2, or 4 learning sessions), Feedback (with or without feedback), Testing (70% retrieval trials or 30%), and Multimodality (unimodal or multimodal; Figs 3 and 4). Dependent variable was the proportion of correctly recalled words during the testing session.

Fig 3. Estimation Plots for the Learning Principles Via Cumming Plots. Upper row shows individual participant data in a swarmplot for unpaired data and a slopegraph for paired data. For unpaired data the mean $\pm$ standard deviation are shown as gapped lines. Lower row shows unpaired or paired mean differences as a bootstrap sampling distribution, with the dot indicating the mean difference and the ends of the error bars the 95% confidence interval.

Fig 4. Pairwise Interaction Plots Between Learning Principles. Values are offset horizontally to avoid over-plotting of error bars. Error bars indicate non-parametrically bootstrapped 95% confidence intervals.

We found a main effect for the factor Spacing ($F[2,76] = 8.51, p = .0005, \eta_p^2 = 0.18$).

In support of H1, participants in which learning was distributed the most (4 sessions) had the

highest recall performance ($M = 77.2, SD = 29$). Performance was intermediate in participants who learned during two sessions ($M = 59.1, SD = 35.3$) and lowest in the massed learning condition (1 session; $M = 52.5, SD = 37$; see Fig 3A). The ANOVA also revealed a main effect of corrective Feedback ($F[1,76] = 21.38, p < .0001, \eta_p^2 = 0.22$; see Fig 3B). As hypothesized (H2), the recall performance was higher ($M = 65.6, SD = 35$) on translations to which corrective feedback was provided in the learning phases than on translations without feedback during learning ($M = 60.4, SD = 35.9$).

The main effects for the factors Testing (H3) and Multimodality (H4) were both insignificant ($F_{Testing}[1,76] = 0.31, p_{Testing} = .58, \eta_p^2_{Testing} = 0.004$; $F_{Multimodality}[1,76] = 0.26, p_{Multimodality} = .61, \eta_p^2_{Multimodality} = 0.003$; Figs 3C and D). One potential explanation for the absence of an effect of testing may arise from considering the two-way interactions of the ANOVA (RQ2). Here, a significant interaction between the factors Testing and Feedback was found ($F[1,76] = 14.12, p = .0003, \eta_p^2 = 0.16$; Fig 4E). Recall performance was higher in the feedback vs. no-feedback condition only when combined with a high rate of retrieval trials (0.7) administered during learning. No such difference was found for a low rate of retrieval trials. Thus, as there is no main effect of Testing, it appears that Testing nevertheless improved learning performance, but only in situations when Testing was combined with corrective Feedback. No other two-way interaction reached significance. For an overview of all effects in the ANOVA, see Table 1.

319 **Table 1. ANOVA learning principles**

Effect	<i>df</i>	<i>MSE</i>	<i>F</i>	η_p^2	<i>p.value</i>	
Spacing	2, 76	4143.08	8.51	0.18	0.0005	***
Modality	1, 76	156.01	0.26	0.003	0.61	
Spacing:Modality	2, 76	156.01	0.5	0.01	0.61	
Testing	1, 76	185.77	0.31	0.004	0.58	
Spacing:Testing	2, 76	185.77	1.85	0.05	0.16	
Feedback	1, 76	204.98	21.38	0.22	<.0001	***
Spacing:Feedback	2, 76	204.98	3.11	0.08	0.05	
Modality:Testing	1, 76	87.46	0.37	0.005	0.54	
Spacing:Modality:Testing	2, 76	87.46	1.74	0.04	0.18	
Modality:Feedback	1, 76	125.67	2.83	0.04	0.1	
Spacing:Modality:Feedback	2, 76	125.67	1.14	0.03	0.32	
Testing:Feedback	1, 76	178.79	14.12	0.16	0.0003	***
Spacing:Testing:Feedback	2, 76	178.79	1.21	0.03	0.3	
Modality:Testing:Feedback	1, 76	134.12	2.36	0.03	0.13	
Spacing:Modality:Testing:Feedback	2, 76	134.12	1.28	0.03	0.28	

320 *Note.* *df* = degrees of freedom, *MSE* = mean squared error, η_p^2 = partial eta squared.

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322 Rather than merely looking at the statistical significance, we think that specifically in an
 323 applied context it is crucial to consider effect sizes. Spacing led to 24.7% higher recall when
 324 participants learned in four spaced sessions instead of in one massed session. Corrective
 325 Feedback increased recall by 5.2%. Due to the combination of feedback and testing, recall
 326 gained another 5.8%. The optimal combination of factors levels was four learning sessions,
 327 feedback, and 70% retrieval trials. The observed means of our sample show that this combination
 328 and the one with 30% retrieval trials were at the top, with almost identical values of 78.2% and
 329 78.7% correctly recalled words. The least efficient combination for learning consisted of one

learning session, no feedback, and 70% retrieval trials and led to 49.5% recall. The difference between the observed best and worst combination was thus a boost of 29%.

One issue we had was that subjects were not entirely random assigned to the factor levels of Spacing. To assess a potential confound of Spacing with other subject-specific variables (e.g. motivation, interest, etc.), we conducted a one-way ANOVA of the factor Spacing on learning performance during the first block of the experiment on the retrieval trials only. This block was comparable with respect to Spacing for all participants. Here, a significant effect of Spacing was found ($F[2,75]=3.18$, $p=0.047$). We then conducted the full factorial ANOVA ($3 \times 2 \times 2 \times 2$ for the factors Spacing, Feedback, Modality and Testing) also on performance in retrieval trials of the first block of learning only. Here, the factor Spacing, again, was significant ($F[2,66]=5.32$, $p=0.007$). The factor Feedback ($F[1,66]=60.45$, $p<0.001$) as well as the interaction of Testing and Feedback ($F[1,66]=8.26$, $p=0.005$) were significant. These results are similar to the main analysis above with performance of the final testing session as dependent variable. Together, these results are consistent with the notion of a confound of participant factors with the experimental factor of Spacing. The effects of Feedback and the interaction of Feedback, in contrast, are unaffected by this potential confound.

Exploratory analyses: learning and testing direction

Each word pair was learned in one direction, either L1-to-L2 or L2-to-L1. Furthermore, since participants performed the recall task in both directions, we could also assess effects of testing direction and the interaction between learning direction and testing direction. This resulted in an additional ANOVA with six factors, adding learning direction and testing directions to the model.

Learning direction had a substantial effect on recall performance ($F[1,76] = 28.61, p < .0001, \eta_p^2 = 0.27$, see Fig 5A), where the words which participants learned in the direction L1-to-L2 ($M = 66.2, SD = 34.4$) were recalled better than those in the direction L2-to-L1 ($M = 59.9, SD = 36.3$). Adding learning direction to the design features described above we observe a difference of 38% between best and worst combinations of features of the learning app (see Table 2). Regarding testing direction, recall performance was generally higher for the direction L2-to-L1 ($M = 72.0, SD = 31.9$) as compared to L2-to-L1 ($M = 54.0, SD = 36.7, F[1,76] = 233.38, p < .0001, \eta_p^2 = 0.75$).

Fig 5. Estimation Plots and Interaction Plot for Learning and Testing Direction. A)

Estimation plots. Upper row shows paired individual participant data in slopegraphs. Lower row shows paired mean differences as a bootstrap sampling distribution, with the dot indicating the mean difference and the ends of the error bars indicating the 95% confidence interval. C) Interaction plot. Values are offset horizontally to avoid over-plotting of error bars. Error bars indicate bootstrapped 95% confidence intervals.

Table 2. Proportions of correctly recalled word pairs in combinations of Spacing, Feedback, Testing, and learning direction

Feedback	Testing	Learning direction	Spacing		
			1	2	4
<i>No feedback</i>	30%	<i>L2-to-L1</i>	50.31	54.67	75.62
<i>No feedback</i>	70%	<i>L2-to-L1</i>	44.14	48.67	71.91
<i>No feedback</i>	30%	<i>L1-to-L2</i>	52.47	58.67	80.25
<i>No feedback</i>	70%	<i>L1-to-L2</i>	54.94	56.00	75.93
<i>Feedback</i>	30%	<i>L2-to-L1</i>	46.60	57.67	75.62
<i>Feedback</i>	70%	<i>L2-to-L1</i>	54.94	63.00	74.38
<i>Feedback</i>	30%	<i>L1-to-L2</i>	55.25	62.67	81.79
<i>Feedback</i>	70%	<i>L1-to-L2</i>	61.11	71.67	82.10

Note. Proportions of correctly recalled word pairs in specific factor combinations over all participants. Each participant learned 6 of the 48 word pairs in each of the 8 shown within-subjects factor combinations (Feedback x Testing x Learning direction). Minimal and maximal values are set in bold font.

We further found an interaction between learning direction and testing direction ($F[1,76] = 105.74, p < .0001, \eta_p^2 = 0.58$; see Fig 5C); words learned in the direction L2-to-L1 were recalled much better when the testing direction matched. For words learned in the direction

L1-to-L2, the recall difference was much smaller and recall was actually higher when the testing direction did not match. The complete results table for this exploratory analysis is available in the Supporting Information (Table S2).

Covariates age, number of trials, and motivation

We checked the influence of the potential covariates age, number of trials, and motivational factors. Performance in cued recall tasks usually dwindles with higher age (Park et al., 1996). To control for potential age effects, we ran an ANCOVA adding age as a covariate to our main model of learning principles. There was a significant age effect ($F[1,73] = 21.68, p < .0001, \eta_p^2 = 0.23$), but the main results of the learning principles remained virtually identical when controlling for age.

The number of trials the participants saw during their learning sessions depended on how quickly they pressed the button to continue to the next trial (in learning trials) or entered their answers (in retrieval trials). Therefore, the number of trials varied substantially between subjects ($M = 1071, SD = 386, range: 338 - 2213$). To check whether this had an effect on recall itself and whether it influenced the findings of our main model, we ran another ANCOVA, adding number of trials as a covariate. While we found a significant effect of number of trials ($F[1,73] = 7.56, p = .008, \eta_p^2 = 0.09$), the other results remained similar to the main model.

Before the first learning session, we assessed motivation related to the learning task. Two of the motivational factors in the questionnaire we used, namely fear of failure and success seeking, are related to tasks described as question-led fact learning, a definition into which our vocabulary learning task seems to fit (Rheinberg et al., 2001). We consequently ran two additional models including each of these factors in turn as a covariate, but there were no significant effects of fear of failure ($F[1,69] = 0, p = .95, \eta_p^2 < 0.0001$) or success seeking

($F[1,62] = 0.13, p = 0.72, \eta_p^2 = 0.002$) and the general results were similar to those of the main model.

Discussion

We investigated whether four learning principles (Spacing, Feedback, Testing, Multimodality) derived from fundamental memory research can be used to optimize a web-application in a real-world digital context for vocabulary learning. Varying the presence/absence or parameters of each of these principles independently, we find that Spacing and the presence of corrective Feedback & Testing together significantly boost learning by 29%. Our results hence demonstrate that informing the development of ICT applications with knowledge from basic memory research can significantly ameliorate their efficiency.

We found an increased recall of approximately 25% due to *Spacing*, which is in the medium range of what previous studies with vocabulary learning paradigms report (Bloom & Shuell, 1981; Cepeda et al., 2009; Lotfolahi & Salehi, 2017; Nakata, 2015). The range of reported spacing effects in studies with L2 vocabulary is rather large as effects between 13% and 35% have been reported. Of course, different study designs and learning intensity are likely origins of this variation. One study that used similar conditions to those in ours (3 day retention interval; fixed ISI of 2 days; 4 learning sessions; first learning session lasted about 30 minutes; 40 word pairs; computer-based flash-card app) found a difference of almost 50% in recall between the uniformly distributed and massed learning conditions (Cull, 2000). A likely reason for a higher effect of spacing than in our study is that they used uncommon-common L1 word pairs instead of L2 vocabulary and the learning time was not fixed. Our significant effect of Spacing, however, has to be taken with a grain of salt since participants were sometimes non-

randomly assigned to the levels of Spacing to due to scheduling constraints. A potential confound of Spacing with unknown participant factors cannot be ruled out.

In comparison to previous studies, we found a rather small benefit of giving corrective *Feedback* to improve vocabulary learning (5.2% higher recall for feedback vs. no feedback). It seems noteworthy that only few comparable studies exist that report the difference between corrective feedback and no feedback conditions in vocabulary learning experiments. One such study assessing five different feedback conditions did not report a significant effect (Pashler et al., 2005) while another reported increases in recall performance by immediate feedback as 11% and 18% (Metcalf et al., 2009).

In our results, *Testing* influenced performance in an interaction together with *Feedback*. Participants could only profit from retrieval trials when they received feedback. This interaction was discussed already by Roediger & Butler (2011), though they reported that testing was often effective even when no feedback is given. To explore this further, one could also incorporate more levels for each factor, for example an option with simple right/wrong feedback (non-corrective) or with a rewrite variant, where subjects have to write out the correct answer directly after they got the corrective feedback. This might lead to deeper processing of the feedback.

To our surprise, *Multimodality* did not improve recall in our experiment. To put this finding into perspective, we can look at comparable computer assisted language learning studies. These often-investigated glosses and annotations in regard to multimodal presentation. One exemplary study found that combined text and image annotations outperformed those with text only but adding videos did not and emphasized the need to isolate the types of annotations in further studies and suggested the audio modality for further investigation (Chun & Plass, 1996). Further support for the use of images together with written definitions in vocabulary learning

was found by another research group but their participants performed poorer when spoken text was added to written text instructions (Kim & Gilman, 2008). These researchers theorized that the problem might be that their participants were used to learning new vocabulary without knowing the pronunciation as is often the case for Korean native speaking participants who learn English. Thus, the additional spoken word sounds might have distracted rather than helped. This might not be transferable to native German speakers in Switzerland who are used to focusing on the pronunciation of new vocabulary in language classes. A similar study reported no difference between text-only, image-only and combined text and image glosses (Yanguas, 2009). Overall, these mixed findings regarding multimodality are consistent with our results indicating no significant difference in the multimodality condition. The discussion of optimal learning environments by Moreno and Mayer might give us further clues about why we did not find an effect in our multimodal condition (Moreno & Mayer, 2007). They cautioned against delivering both verbal and non-verbal stimuli through the same modality (e.g. written word and images), since this could overload the learners' cognitive capacity (Low & Sweller, 2014; Mayer & Fiorella, 2014).

Our findings add additional evidence for the advantage of the L1-to-L2 learning direction in a delayed recall test. In 2002, one study found that participants who had learned in the direction L1-to-L2 recalled less in an immediate test, but then performed marginally better one week later in comparison to those in the L2-to-L1 condition (Schneider et al., 2002). These results are in line with conclusions of another study that found the L1-to-L2 direction to be overall preferable when one learns for both, comprehension and production of the new vocabulary (Griffin & Harley, 1996). In line with our results, one study found an interaction of learning and testing direction: the apparently more difficult learning direction (L1-to-L2) helped

in later recall only if the testing direction matched (Steinel et al., 2007). Together these results may suggest that when a word pair is studied the easier way (L2-to-L1), participants have a hard time recalling and producing the word correctly in the difficult direction (L1-to-L2).

What are these findings telling us about how to develop learning apps? For any real-world application the optimal implementation or combination of these learning principles might vary. Thus, we are well-advised to implement, test, and then update the applications accordingly, possibly through several iterations, to develop better learning tools. That iterative process is what software developers have been doing for decades (Larman & Basili, 2003). However, one might argue that the features a software company wants to optimize might not be those teachers would optimize in a software they hand their pupils. Eventually, success of learning tools should be measured by outcomes like the degree to which it eases the workload of teachers and supports learners. Schools or governments can certainly profit from checking for scientifically tested tools, or if such data is not available, to have them tested, before acquiring and distributing them. Our study was motivated by this thought and shows that turning to basic memory research to inform app-design can boost learning quite significantly.

To conclude, three established learning principles, Spacing, corrective Feedback, and Testing in combination with corrective Feedback improved vocabulary learning performance in the context of a web application with which German speakers learned Finnish. Recall improved by 29% when participants could use the learning principles. These findings support our notion that knowledge from fundamental memory research can inform the development of learning applications to improve them.

References

- Benjamin, A. S., & Tullis, J. (2010). What makes distributed practice effective? *Cognitive Psychology*, 61(3), 228–247. <https://doi.org/10.1016/J.COGLPSYCH.2010.05.004>
- Bjork, R. A. (1975). Retrieval as a Memory Modifier: An Interpretation of Negative Recency and Related Phenomena. In R. L. Solso (Ed.), *Information processing and cognition: The Loyola symposium* (pp. 123–144). Halsted Press.
<http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.694.8821>
- Bjork, R. A. (1994). Memory and metamemory considerations in the training of human beings. In J. Metcalfe & A. P. Shimamura (Eds.), *Metacognition: Knowing about knowing* (pp. 185–205). MIT Press.
- Bjork, R. A., & Kroll, J. F. (2015). Desirable Difficulties in Vocabulary Learning. *The American Journal of Psychology*, 128(2), 241–252. <https://doi.org/10.5406/amerjpsyc.128.2.0241>
- Bloom, K. C., & Shuell, T. J. (1981). Effects of Massed and Distributed Practice on the Learning and Retention of Second-Language Vocabulary. *The Journal of Educational Research*, 74(4), 245–248. <https://doi.org/10.1080/00220671.1981.10885317>
- Carpenter, S. K., Cepeda, N. J., Rohrer, D., Kang, S. H. K., & Pashler, H. (2012). Using Spacing to Enhance Diverse Forms of Learning: Review of Recent Research and Implications for Instruction. *Educational Psychology Review*, 24(3), 369–378.
<https://doi.org/10.1007/s10648-012-9205-z>
- Cepeda, N. J., Coburn, N., Rohrer, D., Wixted, J. T., Mozer, M. C., & Pashler, H. (2009). Optimizing Distributed Practice. *Experimental Psychology*, 56(4), 236–246.
<https://doi.org/10.1027/1618-3169.56.4.236>
- Cepeda, N. J., Pashler, H., Vul, E., Wixted, J. T., & Rohrer, D. (2006). Distributed practice in

- 516 verbal recall tasks: A review and quantitative synthesis. *Psychological Bulletin*, 132(3),
517 354–380. <https://doi.org/10.1037/0033-2909.132.3.354>
- 518 Chang, W., Cheng, J., Allaire, J. J., Xie, Y., & McPherson, J. (2018). *shiny: Web Application*
519 *Framework for R*. <https://cran.r-project.org/package=shiny>
- 520 Cheung, A. C. K., & Slavin, R. E. (2013). The effectiveness of educational technology
521 applications for enhancing mathematics achievement in K-12 classrooms: A meta-analysis.
522 *Educational Research Review*, 9, 88–113. <https://doi.org/10.1016/J.EDUREV.2013.01.001>
- 523 Chun, D. M., & Plass, J. L. (1996). Effects of multimedia annotations on vocabulary acquisition.
524 *Modern Language Journal*, 80(2), 183–198. [https://doi.org/10.1111/j.1540-](https://doi.org/10.1111/j.1540-4781.1996.tb01159.x)
525 [4781.1996.tb01159.x](https://doi.org/10.1111/j.1540-4781.1996.tb01159.x)
- 526 Cull, W. L. (2000). Untangling the benefits of multiple study opportunities and repeated testing
527 for cued recall. *Applied Cognitive Psychology: The Official Journal of the Society for*
528 *Applied Research in Memory and Cognition*, 14(3), 215–235.
529 [https://doi.org/10.1002/\(SICI\)1099-0720\(200005/06\)14:3<215::AID-ACP640>3.0.CO;2-1](https://doi.org/10.1002/(SICI)1099-0720(200005/06)14:3<215::AID-ACP640>3.0.CO;2-1)
- 530 Delaney, P. F., Verkoeijen, P. P. J. L., & Spigel, A. (2010). Spacing and Testing Effects: A
531 Deeply Critical, Lengthy, and At Times Discursive Review of the Literature. In *Psychology*
532 *of Learning and Motivation* (Vol. 53, pp. 63–147). Academic Press.
533 [https://doi.org/10.1016/S0079-7421\(10\)53003-2](https://doi.org/10.1016/S0079-7421(10)53003-2)
- 534 European Commission. (2019). *2nd Survey of schools: ICT in education - Objective 1:*
535 *Benchmarking progress in ICT in schools*. Publications Office of the European Union,
536 2019. <https://doi.org/10.2759/23401>
- 537 Futuresource Consulting. (2016, April 14). *Education Technology Hardware Spend in K-12*
538 *Increases by 7% in 2015*. <https://futuresource-consulting.com/press-release/education->

- 539 technology-press/education-technology-hardware-spend-in-k-12-increases-by-7-in-2015/
540 Godwin-Jones, R. (2010). Emerging technologies from memory palaces to spacing algorithms:
541 Approaches to second-language vocabulary learning. *Language Learning and Technology*,
542 14(2), 4–11.
- 543 Greve, A., Cooper, E., Kaula, A., Anderson, M. C., & Henson, R. (2017). Does prediction error
544 drive one-shot declarative learning? *Journal of Memory and Language*, 94, 149–165.
545 <https://doi.org/10.1016/j.jml.2016.11.001>
- 546 Griffin, G., & Harley, T. A. (1996). List learning of second language vocabulary. *Applied*
547 *Psycholinguistics*, 17(04), 443. <https://doi.org/10.1017/S0142716400008195>
- 548 Kast, M., Baschera, G. M., Gross, M., Jäncke, L., & Meyer, M. (2011). Computer-based learning
549 of spelling skills in children with and without dyslexia. *Annals of Dyslexia*, 61(2), 177–200.
550 <https://doi.org/10.1007/s11881-011-0052-2>
- 551 Kast, M., Meyer, M., Vögeli, C., Gross, M., & Jäncke, L. (2007). Computer-based multisensory
552 learning in children with developmental dyslexia. *Restorative Neurology and Neuroscience*,
553 25(3–4), 355–369. <http://www.ncbi.nlm.nih.gov/pubmed/17943011>
- 554 Kim, D., & Gilman, D. A. (2008). Effects of text, audio, and graphic aids in multimedia
555 instruction for vocabulary learning. *Educational Technology and Society*, 11(3), 114–126.
556 <https://www.jstor.org/stable/pdf/jeductechsoci.11.3.114>
- 557 Kornell, N., Castel, A. D., Eich, T. S., & Bjork, R. A. (2010). Spacing as the friend of both
558 memory and induction in young and older adults. *Psychology and Aging*, 25(2), 498–503.
559 <https://doi.org/10.1037/a0017807>
- 560 Larman, C., & Basili, V. R. (2003). Iterative and incremental developments. a brief history.
561 *Computer*, 36(6), 47–56. <https://doi.org/10.1109/MC.2003.1204375>

- 562 Lisman, J. E., & Grace, A. A. (2005). The Hippocampal-VTA Loop: Controlling the Entry of
563 Information into Long-Term Memory. *Neuron*, 46(5), 703–713.
564 <https://doi.org/10.1016/j.neuron.2005.05.002>
- 565 Lotfolahi, A. R., & Salehi, H. (2017). Spacing effects in vocabulary learning: Young EFL
566 learners in focus. *Cogent Education*, 4(1). <https://doi.org/10.1080/2331186X.2017.1287391>
- 567 Low, R., & Sweller, J. (2014). The Modality Principle in Multimedia Learning. In R. E. Mayer
568 (Ed.), *The Cambridge Handbook of Multimedia Learning* (2nd ed.). Cambridge University
569 Press.
- 570 Mayer, R. E., & Fiorella, L. (2014). Principles for managing essential processing multimedia
571 learning: Segmenting, pretraining, and modality principles. In R. E. Mayer (Ed.), *The*
572 *Cambridge Handbook of Multimedia Learning* (2nd ed.). Cambridge University Press.
- 573 Metcalfe, J. (2017). Learning from Errors. *Annual Review of Psychology*, 68(1), 465–489.
574 <https://doi.org/10.1146/annurev-psych-010416-044022>
- 575 Metcalfe, J., Kornell, N., & Finn, B. (2009). Delayed versus immediate feedback in children's
576 and adults' vocabulary learning. *Memory & Cognition*, 37(8), 1077–1087.
577 <https://doi.org/10.3758/MC.37.8.1077>
- 578 Moreno, R., & Mayer, R. (2007). Interactive Multimodal Learning Environments. *Educational*
579 *Psychology Review*, 19(3), 309–326. <https://doi.org/10.1007/s10648-007-9047-2>
- 580 Morris, C. D., Bransford, J. D., & Franks, J. J. (1977). Levels of processing versus transfer
581 appropriate processing. *Journal of Verbal Learning and Verbal Behavior*, 16(5), 519–533.
582 [https://doi.org/10.1016/S0022-5371\(77\)80016-9](https://doi.org/10.1016/S0022-5371(77)80016-9)
- 583 Murray, M. M., & Sperdin, H. F. (2010). Single-Trial Multisensory Learning and Memory
584 Retrieval. In J. Kaiser & M. J. Naumer (Eds.), *Multisensory Object Perception in the*

- 585 *Primate Brain* (pp. 191–208). Springer New York. <https://doi.org/10.1007/978-1-4419->
586 5615-6
- 587 Nakata, T. (2015). EFFECTS OF EXPANDING AND EQUAL SPACING ON SECOND
588 LANGUAGE VOCABULARY LEARNING. *Studies in Second Language Acquisition*,
589 37(04), 677–711. <https://doi.org/10.1017/S0272263114000825>
- 590 Park, D. C., Smith, A. D., Lautenschlager, G., Earles, J. L., Frieske, D., Zwahr, M., & Gaines, C.
591 L. (1996). Mediators of long-term memory performance across the life span. *Psychology*
592 *and Aging*, 11(4), 621–637. <https://doi.org/10.1037//0882-7974.11.4.621>
- 593 Pashler, H., Cepeda, N. J. N., Wixted, J. T., Rohrer, D., ... J. W.-... P. L., & 2005, U. (2005).
594 When does feedback facilitate learning of words? *Journal of Experimental Psychology:*
595 *Learning, Memory, and Cognition*, 31(1), 3–8. <https://doi.org/10.1037/0278-7393.31.1.3>
- 596 R Core Team. (2018). *R: A Language and Environment for Statistical Computing*. [https://www.r-](https://www.r-project.org/)
597 [project.org/](https://www.r-project.org/)
- 598 Reber, T. P., & Rothen, N. (2018). Educational App-Development needs to be informed by the
599 Cognitive Neurosciences of Learning & Memory. *Npj Science of Learning*, 3(1), 22.
600 <https://doi.org/10.1038/s41539-018-0039-4>
- 601 Rheinberg, F., Vollmeyer, R., & Burns, B. D. (2001). FAM: Ein Fragebogen zur Erfassung
602 aktueller Motivation in Lehr- und Leistungssituationen [FAM: A questionnaire to assess
603 motivation in situations of learning and performing]. *Diagnostica*, 2(January 2015), 57–66.
604 <https://doi.org/10.1026//0012-1924.47.2.57>
- 605 Roediger, H. L., & Butler, A. C. (2011). The critical role of retrieval practice in long-term
606 retention. *Trends in Cognitive Sciences*, 15(1), 20–27.
607 <https://doi.org/10.1016/j.tics.2010.09.003>

- 608 Roediger, H. L., & Pyc, M. A. (2012). Inexpensive techniques to improve education: Applying
609 cognitive psychology to enhance educational practice. *J. Appl. Res. Mem. Cogn.*, 1(4), 242–
610 248. <https://doi.org/10.1016/j.jarmac.2012.09.002>
- 611 Rowland, C. A. (2014). The effect of testing versus restudy on retention: a meta-analytic review
612 of the testing effect. *Psychol. Bull.*, 140(6), 1432–1463. <https://doi.org/10.1037/a0037559>
- 613 Schneider, V. I., Healy, A. F., & Bourne, L. E. (2002). What Is Learned under Difficult
614 Conditions Is Hard to Forget: Contextual Interference Effects in Foreign Vocabulary
615 Acquisition, Retention, and Transfer. *Journal of Memory and Language*, 46(2), 419–440.
616 <https://doi.org/10.1006/JMLA.2001.2813>
- 617 Settles, B., & Meeder, B. (2016). A Trainable Spaced Repetition Model for Language Learning.
618 *Proceedings of the Association for Computational Linguistics (ACL)*, 1848–1858.
619 <https://doi.org/10.18653/v1/P16-1174>
- 620 Shams, L., & Seitz, A. R. (2008). Benefits of multisensory learning. *Trends in Cognitive*
621 *Sciences*, 12(11), 411–417. <https://doi.org/10.1016/J.TICS.2008.07.006>
- 622 Steinel, M. P., Hulstijn, J. H., & Steinel, W. (2007). SECOND LANGUAGE IDIOM
623 LEARNING IN A PAIRED-ASSOCIATE PARADIGM: Effects of Direction of Learning,
624 Direction of Testing, Idiom Imageability, and Idiom Transparency. *Studies in Second*
625 *Language Acquisition*, 29(03), 449–484. <https://doi.org/10.1017/S0272263107070271>
- 626 Steiner, M., Phillips, N., & Trutmann, K. (2018). *ShinyPsych: An easy way to program*
627 *psychology experiments using Shiny*. <https://github.com/mdsteiner/ShinyPsych>
- 628 Sung, Y.-T., Chang, K.-E., & Liu, T.-C. (2016). The effects of integrating mobile devices with
629 teaching and learning on students' learning performance: A meta-analysis and research
630 synthesis. *Computers & Education*, 94, 252–275.

<https://doi.org/10.1016/J.COMPEDU.2015.11.008>

Tamim, R. M., Bernard, R. M., Borokhovski, E., Abrami, P. C., & Schmid, R. F. (2011). What

Forty Years of Research Says About the Impact of Technology on Learning. *Review of*

Educational Research, 81(1), 4–28. <https://doi.org/10.3102/0034654310393361>

Weinstein, Y., Madan, C. R., & Sumeracki, M. A. (2018). Teaching the science of learning.

Cognitive Research: Principles and Implications, 3(1). [https://doi.org/10.1186/s41235-017-](https://doi.org/10.1186/s41235-017-0087-y)

0087-y

Wilkinson, L., Tai, Y. F., Lin, C. S., Lagnado, D. A., Brooks, D. J., Piccini, P., & Jahanshahi, M.

(2014). Probabilistic classification learning with corrective feedback is associated with in

vivo striatal dopamine release in the ventral striatum, while learning without feedback is

not. *Human Brain Mapping*, 35(10), 5106–5115. <https://doi.org/10.1002/hbm.22536>

Yanguas, I. (2009). Multimedia glosses and their effect on L2 text comprehension and

vocabulary learning. *Language Learning and Technology*, 13(2), 48–67.

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Supporting information

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S1 Table. ANOVA four learning principles in subsample (excluding the remote-tested

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participants)

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S2 Table. ANOVA four learning principles, learning direction, and test direction

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S3 Table. Mean numbers of trials per word pair and participant in all conditions

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S4 Table. ANOVA learning principles' effects on frequency of trials differences among

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stimuli