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Changing dentists' carious tissue removal behavior: Qualitative study and behavioral change simulation experiment

L.-M. Jeggle[a], S.R. Baker[b], F. Schwendicke[a,*]

[a] Department of Operative and Preventive Dentistry, Charité – Universitätsmedizin Berlin, Campus Benjamin Franklin, Aßmannshauser Str. 4-6, 14197 Berlin, Germany
[b] Unit of Oral Health, Dentistry and Society, School of Clinical Dentistry, University of Sheffield, UK

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ABSTRACT

Objectives: We aimed to understand why German dentists remain reluctant about selective carious tissue removal (SE), and to develop and test two interventions for changing dentists' behavior.
Methods: Ten one-to-one interviews with German dentists were conducted, and identified themes linked to the Behavioral Change Wheel to develop two interventions. The intervention "Guideline" summarized a scientific statement on SE, while the intervention "Tool" simulated dentists having a removal tool (self-limiting handpiece) allowing them to reliably perform SE. For testing these interventions, a postal behavioral-change simulation-experiment was performed on German dentists (n = 1226/intervention), delivered via sealed envelopes. Dentists were first, without knowledge of the intervention, asked to fill out a questionnaire, including a question on their simulated removal behavior in deep lesions in vital teeth, measured via the dentin hardness dentists would leave close to the pulp. After opening the sealed envelope and receiving the simulated intervention, dentists filled out a second identical questionnaire.
Results: Based on identified barriers (lack of guidelines, discrepancy between established and "new" knowledge, lack of routine) and facilitators (understanding the biological foundations for SE, knowing it was evidence-based, having reliable criteria for determining the endpoint of SE), the two interventions were developed. 504 dentists participated in the experiment (response rate:24.9%). For both interventions, the outcome behavior improved significantly after the intervention ($p < 0.001$), with 29.6% (guideline) and 17.9% (tool) changing their behavior towards SE, respectively. There were no significant differences in the outcome behavior between the two interventions ($p = 0.933$).
Conclusion: Systematically developed behavior-change interventions may be efficacious to improve the uptake of SE.
Clinical significance: Understanding the barriers and facilitators for applying SE facilitates the development of interventions which may be efficacious for changing carious tissue removal.

1. Introduction

Dental caries is the most prevalent disease of humankind, burdening billions of people and generating substantial direct and indirect costs [1,2]. Based on an understanding of caries as an infectious disease, the traditional management of carious lesions (demineralized and/or bacterially contaminated tissue) involved surgical removal of carious tissue until only hard dentin remained everywhere in the cavity. Such non-selective or "complete" carious tissue removal comes with significant risks for the pulp if deep carious lesions are managed, as pulp exposure and complications are frequent, oftentimes requiring further endodontic interventions long-term [3,4].

The current understanding of caries considers not the presence but the cariogenic activity of dental biofilms as most relevant [5]. A large number of studies have shown that sealing biofilms, for example, allows controlling their activity by restricting the carbohydrate intake of sealed bacteria [6,7]. Consequently, in deep carious lesions, selective carious tissue removal (SE) is now recommended over non-selective removal. SE removes carious tissue until only hard tissue remains in the periphery of the cavity (to ensure longevity to the subsequently placed restoration), and leaves soft, leathery or firm dentin (depending on the lesion depth) in proximity of the pulp. Robust evidence supports SE for managing especially deep carious lesions [8].

However, the majority of dentists in most countries in the world has

* Corresponding author at: Charité – Universitätsmedizin Berlin, Humboldt-Universität zu Berlin, and Berlin Institute of Health, Department for Operative and Preventive Dentistry, Aßmannshauser Str. 4-6, 14197 Berlin, Germany.
E-mail address: falk.schwendicke@charite.de (F. Schwendicke).

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not unequivocally adopted SE [9]. A number of factors have been found to be associated with dentists' carious tissue removal behavior, for example their age, their understanding of the disease caries and its pathogenesis, and the rationale behind different carious tissue removal strategies (non-selective, selective). Also, guidelines, peers and the dentists' professional identity as well as environmental factors (financial or regulatory) appear to play a role [10]. To understand how these factors shape decision-making in a specific setting and to deduce interventions for changing dentists' behavior, qualitative studies are needed. Ideally, these studies should employ a theoretical framework, as this helps to comprehensively and systematically evaluate the factors underlying specific behaviors [10]. Building on such qualitative data, it is then possible to deduce behavior change interventions, and to test them, for example in behavior change simulation experiments. Such experiments simulate the delivery of a behavior change intervention, for example via a vignette, and then theoretically explore what kind of behavior change could be expected if the intervention was delivered not only theoretically, but also practically.

We aimed to understand the facilitators and barriers for performing SE in Germany using qualitative interviews, and to use this information to develop and test two interventions for changing dentists' SE-related behavior in a simulation experiment. We hypothesized that one or both interventions would significantly change dentists' simulated carious tissue removal behavior.

2. Methods

The reporting of this study follows the COREQ guideline and the CONSORT extension for simulation studies [11,12], and has been ethically approved (Charité – Universitätsmedizin Berlin EA2/137/14).

2.1. Aim, design and setting

The aim of this study was to develop and test two interventions for changing dentists' simulated carious tissue removal behavior. The study was based in Germany and a mixed-methods design was used. An overview of the study is summarized in Fig. 1.

In the first part of the study, 10 semi-structured one-to-one interviews (see Appendix Material 1 for the interview schedule) were performed. Content analysis was performed on the qualitative data using the Theoretical Domains Framework (TDF) as a guide to identify barriers and facilitators for performing SE. The TDF builds on a number of domains (Table 1) and has been used in a few studies in dentistry to date [9,13–15]. Note that we modified the TDF domains, eventually using only ten of them, according to the aims and scope of the study. The TDF can be linked with the Behavior Change Wheel (BCW, Fig. 2) [16] and the Capability-Opportunity-Motivation-Behavior Model (COM-B model) [17,18,44]. The COM-B model assumes that capability (psychological or physical ability to enact behaviour), opportunity (physical and social environment that enables the behaviour), and motivation (reflective and automatic mechanisms that activate or inhibit behaviour) all affect each other and jointly affect behavior [18]. For changing behavior one or more of the components need to be altered by an intervention. The COM-B Model builds the centre of the BCW. Using the Behavior Change Technique Taxonomy version 1 (BCTTv1), two specific interventions targeting identified facilitators and barriers were developed [18]. These interventions are described in detail below.

In the second part of the study, a behavioral change simulation experiment was carried out to examine the effect of each intervention on the outcome, which was simulated carious tissue removal behavior, measured via the dentin hardness dentists would leave close to the pulp in vital teeth with deep carious lesions (see below for details)

2.2. Qualitative interviews

2.2.1. Research team and reflexivity

This study was conducted by a research team involving a dental clinician (LMJ), an experienced psychologist and qualitative researcher (SB) and a dental health researcher with a focus on carious tissue removal (FS). They jointly designed the interview schedule. The data analysis was performed by LMJ, assisted by SB. All three researchers acted as an expert panel to determine how to apply the TDF [14]. Interviews were conducted by LMJ. As she had no previous training in

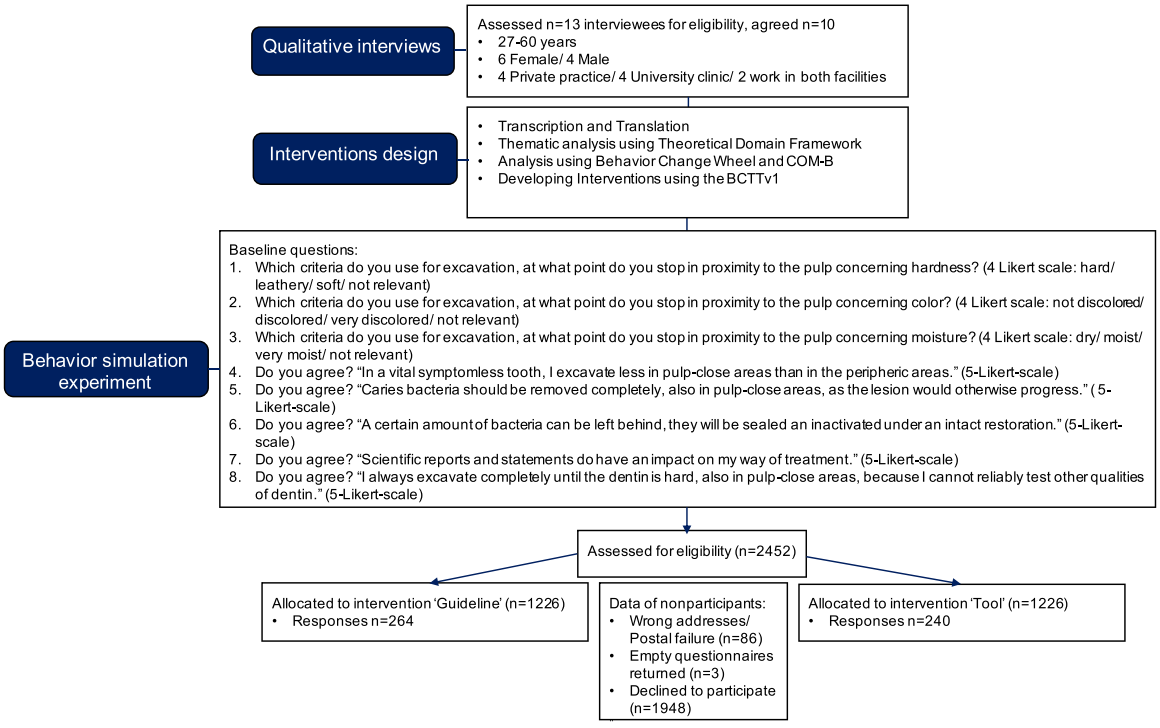

Fig. 1. Flowchart of the study.

Table 1
Domains of the Theoretical Domains Framework (TDF) [21]. Note that we used only ten domains in the present study according to our aims and the scope of the study, these are indicated by an asterisk (*).

Domain	Definition
Knowledge*	An awareness of the existence of something
Skills*	An ability or proficiency acquired through practice
Social/ Professional and Identity *	A coherent set of behaviors and displayed personal qualities of an individual in a social or work setting
Beliefs about Capabilities*	Acceptance of the truth, reality, or validity about an ability, talent, or facility that a person can put to constructive use
Optimism	The confidence that things will happen for the best, or that desired goals will be attained
Beliefs about Consequences*	Acceptance of the truth, reality, or validity about outcomes of a behavior in a given situation
Reinforcement	Increasing the probability of a response by arranging a dependent relationship, or contingency, between the response and a given stimulus
Intention*	A conscious decision to perform a behavior or a resolve to act in a certain way
Goals*	Mental representation of outcomes or end states that an individual wants to achieve
Memory, Attention and Decision Process	The ability to retain information, focus selectively on aspects of the environment and choose between more alternatives
Environmental Context and Resources *	Any circumstance of a person's situation or environment that discourages or encourages the development of skills and abilities, independence, social competence, and adaptive behavior
Social Influences	Those interpersonal processes that can cause an individual to change their thoughts, feelings or behaviors
Emotion*	A complex reaction pattern, involving experiential, behavioral, and psychological elements, by which the individual attempts to deal with a personally significant matter or event
Behavioral Regulation	Anything aimed at managing or changing objectively observed or measured actions

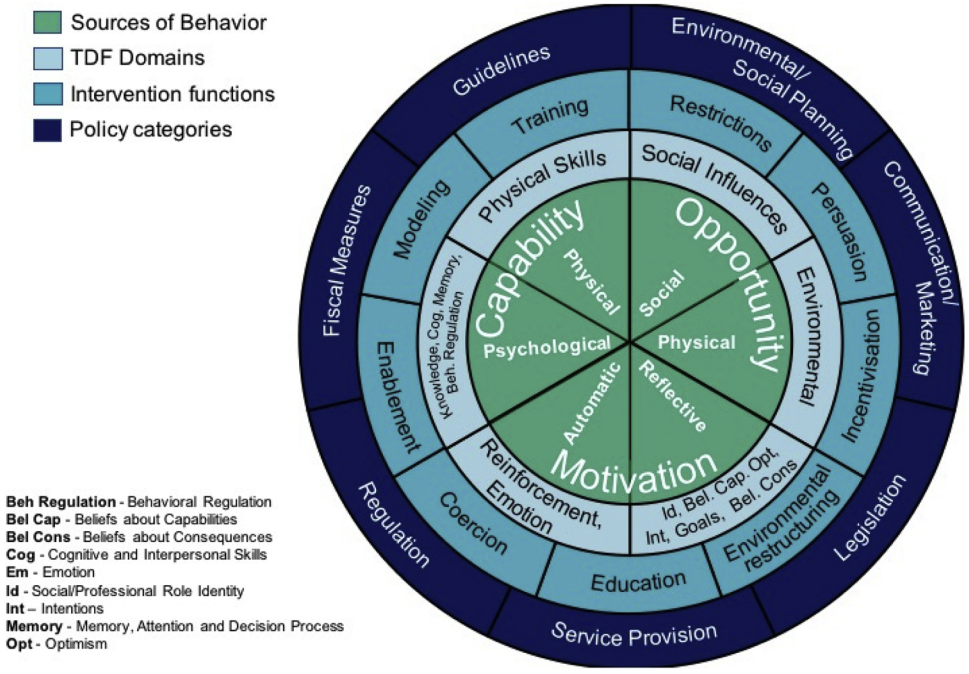

Fig. 2. The Behaviour Change Wheel (BCW) [26]. The first hub of the wheel contains the Capability-Oportunity-Motivation-Behavior Model (COM-B model) and shows possible sources of behavior, that could be identified for change by intervention. Based on the analysis of the first hub, Theoretical Domains Framework (TDF) domains in the second hub help to further identify intervention functions, which are located in the third hub. The fourth hub offers policy categories for developing interventions.

performing qualitative interviews, a number of pilot interviews were performed until the interview quality and depth was found appropriate. These also served to assess the suitability of the interview schedule. The interviewees did not have any close relationship to the interviewer. All interviewees were informed about data collection, the background and purpose of the study before consenting to take part in the interviews.

2.2.2. Participant selection

Qualitative interviews are usually not subject to sample size estimations [19]. However, we aimed to include dentists from a variety of backgrounds to increase the range and scope of practice relevant to SE behavior. Dentists were purposively sampled from German registration lists via telephone, or dentists known to the research team were approached informally. We also used snowball sampling [20]. We first approached ten dentists (six female and four male dentists), assuming this sample size to be sufficient to gather a deep understanding of barriers and themes. After sampling and interviewing these ten dentists, data analysis was performed (see below), indicating that a saturation of themes had occurred. Hence, no further dentists were approached.

The age range of the sampled dentists was 27–60 years, with 2–35 (mean 14) years of professional experience. Four dentists worked at university dental schools, four dentists worked in private practices, two dentists worked in both university and private practice. Six dentists were approached in Berlin, four dentists were spread over Germany in smaller cities. The characteristics of non-responders were not recorded separately, and reasons for non-response were not followed up.

2.2.3. Data collection

As described, the interview schedule and data analysis utilized the TDF, which is a tool to explore behavioral change [21] and can be linked with the BCW [22] to derive interventions. The TDF includes 14 domains; these are described in Table 1. As described, only ten of the domains were used here (as indicated in Table 1). Both closed and open-ended questions were used. Interviews were conducted in person (face-to-face in a dental surgery) or by telephone, and audio-recorded. They lasted between approximately 20 min to one hour. No incentives

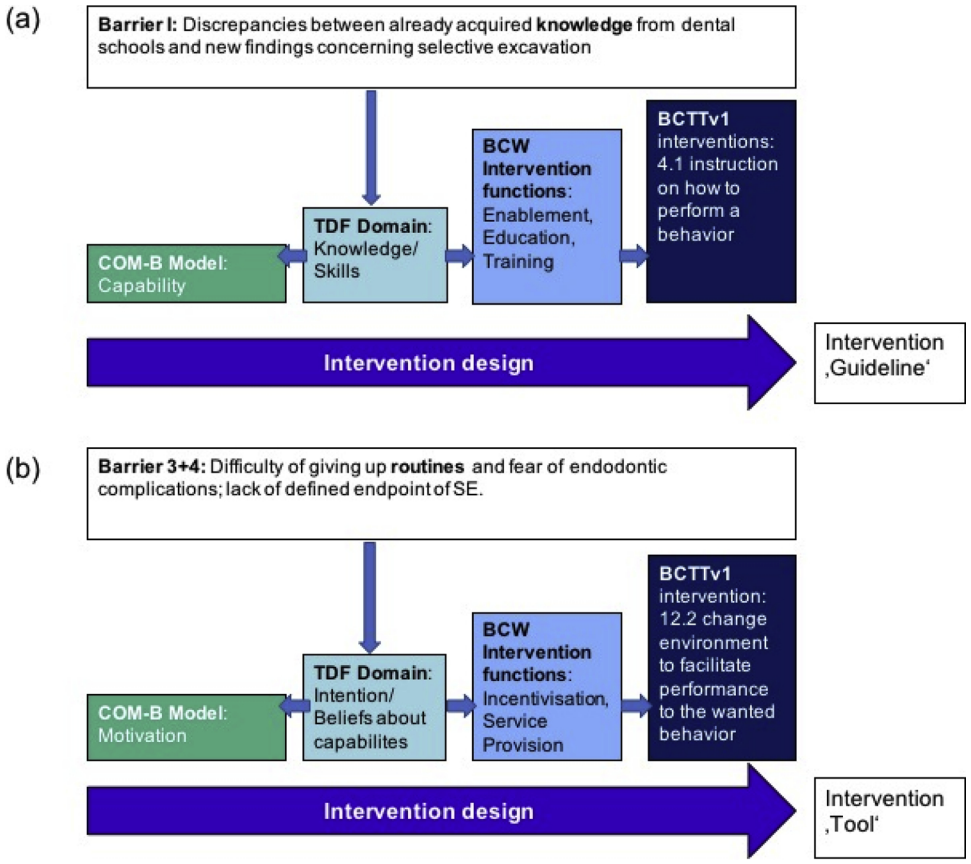

Fig. 3. Intervention development. The two interventions, “Guideline” (a) and “Tool” (b), were developed based on different identified barriers and facilitators. For example, for “Guideline”, the discrepancy between educational and “new” knowledge was a barrier. Using the Theoretical Domains Framework (TDF, which is also the second hub of the Behaviour Change Wheel BCW), we were able to link this barrier to the TDF-domains “Knowledge/skills”. From here, the barriers were linked to the underlying factor in the Capability-Oportunity-Motivation-Behavior-Model (COM-B model, first hub of the Behaviour Change Wheel BCW), which was capability, as well as to an intervention function. Intervention functions can be found in the third hub of the BCW. Function that influence kknowledge included enablement, education, training). Then, the Behavior Change Technique Taxonomy Version 1 (BCTTv1) was used to assign a specific intervention. A similar pathway was taken for the intervention” Tool”.

for participation were provided. The interviews were anonymized and transcribed verbatim [23] by LMJ. Before coding, they were translated to English by one researcher (LMJ) and this translation checked by another (FS). Transcripts were not fed back to interviewees.

2.2.4. Data analysis

Analysis of the data was conducted in a number of stages. First, LMJ analyzed the data by grouping the participants’ responses under the ten used TDF domains and associated constructs. A sample of coded transcripts was sent to SB to check for consistency, and then the remaining coding was conducted by LMJ using ATLAS.ti (Version 1.6.0, ATLAS.ti, Berlin, Germany). The most relevant domains pertaining to the barriers and facilitators of SE were then identified by LMJ and FS.

2.2.5. Interventions design

We applied the BCW [16] and, related to it, the COM-B model [17] and the Behavior Change Technique Taxonomy Version 1 (BCTTv1) [18,24] to derive interventions targeting the specific identified barriers and/or facilitators as summarized in Fig. 3. From each identified barrier and/or facilitator, we were able to link it, using the BCW, to a domain of the COM-B model as well as different TDF domains. A specific barrier/facilitator was then linked to the third hub of the BCW, which contains intervention functions, which can then be related to a policy category (fourth hub) suggesting how to deliver an intervention. For each intervention function and policy, different specific instruments will be available. We used the BCTTv1, which is a comprehensive, coherent and multi-modal catalogue of overall 93 clustered behavior change techniques [25] which can be linked to the BCW, to eventually identify a range of adequate interventions addressing our barriers and/or facilitators.

We decided to design two interventions. Both met the APPEASE Criteria [26] (Acceptability, Practicability, Effectiveness, Cost-effectiveness, Affordability, Safety, Equity). Each intervention addressed different identified barriers and facilitators. The decision to develop only two interventions was made for reasons of practicality and resource restrictions. The intervention “Guideline” summarized the recently published statement of the German Association of Conservative Dentistry on carious tissue removal [27], laying out the biological foundations and the evidence-base behind SE as well as recommending SE in deep lesions in vital teeth. The second intervention, ‘Tool’, simulated the availability of a tool (a self-limiting handpiece) that would help the dentists to reliably and routinely establish a valid endpoint of SE in deep lesions. The tool was assumed to provide feedback on the dentin hardness, and dentists were asked to assume that they would have bought it and could now routinely apply SE in a reliable way. The vignette texts dentists received to simulate the interventions are fully shown in the Appendix Material 2; no further information beyond a neutral text (i.e. no images etc.) was provided.

2.3. Behavioral change simulation experiment

2.3.1. Design

The experiment involved the randomized delivery of one of the two interventions to random dentists in Germany via post. The intervention was delivered in a sealed envelope, together with two questionnaires, each containing a total of eight Likert-scaled questions on dentists’ carious tissue removal behavior. Dentists were asked to fill out one questionnaire before opening the sealed envelope. Afterwards, the envelope was to be opened and the intervention received by reading the simulated intervention vignette. Then, dentists filled out the second, identical questionnaire. Our primary outcome was the simulated behavior change, indicated by the hardness of the dentin dentists would leave close to the pulp in a deep lesion in a tooth with a vital pulp. The questionnaire is given in full Appendix Material 2 and summarized in Fig. 1. Briefly, the questions were as follows, with question 1 being related to the primary outcome:

(1) Which criteria do you use for excavation, at what point do you stop in proximity to the pulp concerning hardness? (4-Likert-scale: hard/ leathery/ soft/ does not matter)
(2) Which criteria do you use for excavation, at what point do you stop in proximity to the pulp concerning color? (4-Likert-scale: not discolored/ discolored/ very discolored/ does not matter)
(3) Which criteria do you use for excavation, at what point do you stop in proximity to the pulp concerning moisture? (4-Likert-scale: dry/ moist/ very moist/ does not matter)
(4) "In a vital symptomless tooth, I excavate differently in pulpal areas than in the periphery." Do you agree? (5-Likert-scale: strongly agree/ agree/ partly agree/ disagree/ strongly disagree)
(5) "Cariogenic bacteria should be removed completely, also in pulpal areas, as the lesion would otherwise process." Do you agree? (5-Likert-scale: strongly agree/ agree/ partly agree/ disagree/ strongly disagree)
(6) "A certain amount of bacteria can be left behind, they will be sealed and inactivated under intact restorations." Do you agree? (5-Likert-scale: strongly agree/ agree/ partly agree/ disagree/ strongly disagree)
(7) "Scientific reports and statements do have an impact on my way of treatment." Do you agree? (5-Likert-scale: strongly agree/ agree/ partly agree/ disagree/ strongly disagree)
(8) "I always excavate non-selectively until the dentin is hard, also in pulp-close areas, because I cannot test other qualities of dentin reliably." Do you agree? (5-Likert-scale: strongly agree/ agree/ partly agree/ disagree/ strongly disagree)*

* In the Group 'Tool', the following question was used after delivering the intervention instead: Now that you do theoretically have a sufficient tool to judge the quality of dentin, would you excavate selectively? (5-Likert-scale: strongly agree/ agree/ partly agree/ disagree/ strongly disagree)

Note that the questionnaire was not validated for its association with actual behavior (actual behavior was beyond our scope). The instrument had been tested for clarity in a number of dentists who were not part of the eventual sample, and revised in details. No formal reliability testing, however, was performed. Also note that the questionnaire did not specify if the scenario was on permanent or primary teeth. This was, as the decision between selective versus non-selective removal is not only one of permanent, but also primary teeth (there are a range of studies showing that the evidence points into a similar direction in both dentitions) [28]. Admittedly, though, in the primary dentition further options (Hall Technique, non-restorative cavity control) may be available [29].

2.3.2. Sample size estimation

Sample size calculation was performed using G*Power (3.1.9.3, Universität Düsseldorf, Germany). Based on a number of studies in the field [30,31], we assumed a mean difference of 10% of our primary outcome (simulated carious tissue removal behavior) after receiving the interventions compared with the baseline (control) behavior, i.e. we assumed that at least 10% of dentists would change their simulated excavation behavior by the intervention. A 10% difference was assumed to be clinically worthwhile, helping to maintain pulpal vitality of thousands of teeth in Germany, and was supported by the reported minimal change to be achieved by behavior change interventions [30,31]. We further assumed a standard deviation of 50% in our primary outcome. Using a two-sided *t*-test and assuming a required power of 1-beta = 0.80 and alpha being 0.05, we estimated 368 responses to be needed to demonstrate the interventional effect of at least one intervention against the control with statistical significance. Assuming a response rate of 30% [32], 1226 dentists were approached per intervention, i.e. a total of 2452 questionnaires were sent. Note that sample size estimation was, for reasons of simplicity, considering the proportion of dentists (in %) changing their behavior towards SE, while the outcome and the statistical analysis considered ordinally scaled data, as described above and below. Based on the fact that we eventually found significant changes in the behavior, our study was nevertheless sufficiently powered.

2.3.3. Randomization

A simple computer-generated sequence was used to both sample the dentists into our study and to assign one of the two interventions. No blocking was performed. As central randomization was performed, and given our study design, allocation concealment was also achieved. Participants were blinded for the test intervention when baseline data was gathered, as the intervention was sent in a separate, sealed envelope as described. Note, however, that we cannot be sure if dentists did really follow this advice; some dentists may have opened the envelope before filling out the first questionnaire. This may introduce bias into our study. Sending the questionnaires after each other and hence avoiding any such bias was impossible given responses being completely anonymized.

2.3.4. Participants and survey

Besides questions on carious tissue removal behavior, we also asked questions on participants' gender, age, practice type and setting. These were used as covariates in our statistical analysis (see below), but also to compare our responders with the target population, which were all general dental practitioners who were clinically active in Germany in 2018 (n = 71.926) [33]. No question on ethnicity, country of training or specialization were included in the questionnaire.

Participants were randomly sampled from a commercially available address registration lists of all dental practitioners without restrictions as to their specialty, sex or age. The surveys were sent out on April 9th 2018; participants had four weeks for completing them. No second postal contact was made to reduce costs. Non-responders could not be followed-up, as returns were anonymized. A total of 86 questionnaires were sent back by the postal services as addresses were wrong and/or dentists were no longer available (Fig. 1).

2.3.5. Statistical analysis

As described, our primary outcome was the simulated carious tissue behavior, measured via the simulated dentin hardness a dentist would leave close to the pulp in deep lesions in vital teeth. The outcome was measured on an ordinal 4-Likert scale (from "hard" = 1 to "firm" = 2 to "soft" = 3 dentin to "hardness does not matter in proximity to the pulp" = 4). The effect of each intervention on the primary outcome was tested by comparing the distribution of responses at baseline versus that after the intervention using the Chi-square test. Also, distributions of the responses to the other seven questions at baseline and after the intervention were compared using the Chi-square test, as were the sociodemographic characteristics of dentists sampled into both interventions and the general dentists in Germany. To test for differences in simulated post-intervention behavior between intervention groups, accounting for the described covariates (namely intervention group, age, years of practical experience, sex), multinomial logistic regression was applied. For the latter, only compete cases (where all covariates were available) could be included. Hence, for this analysis, the sample size was smaller than for the other analyses (n = 387). Statistical analysis was performed using SPSS 20 (IBM, Armonk, USA) plugged into R 3.1 (R foundation).

3. Results

3.1. Qualitative interviews and identified themes

The identified themes were grouped under the TDF domains and constructs. The main findings were as follows, given in exemplary quotes (details can be found in Appendix Material 3):

(1) Knowledge

All of the dentists made comments that could be grouped into the domain 'Knowledge', with most comments made about guidelines. The need for guidelines on SE was the most frequent point made. Most dentists built their treatment on knowledge gained in dental school and could not name any guideline or scientific research on carious tissue removal. Experiences and procedural knowledge were also mentioned by all interviewees. In the domain 'experiences', the fear of endodontic treatment and further complications was frequently mentioned. Procedural knowledge mainly pertained to the uncertainty of the carious tissue removal endpoint. For example:

'*Yes, it (guideline) is helpful and provides certainty for me, because after all I learned it differently before. Everything has to be very firm, then you excavated properly, if not, you leave caries behind. And if that has changed now, and it is written down in a guideline it helps a lot in my professional life.*' *(Dentist No.10)*

'Of course, if I understand the guideline like 'I am allowed to leave caries behind', I'd say of course it is helpful because I absolutely hate endodontic treatment. I'm not specialized in endodontics, in so far I am happy if I can avoid it.' (Dentist No.3)

'I was astonished, we calibrated, excavated teeth (selectively) and had it controlled, if we did it right like it has to be in selective excavation. I was amazed that although I thought I had left something behind, I already went a step to far. So, this is the problem, that there is no clear cut where I have to stop. It is a matter of gut feeling. It is not well defined.' (Dentist No.3)

(2) Skills and capability

Dentists mentioned the use of rosehead burs and the ascertainment of the endpoint of removal as required skills. Dentists were confident to be capable to perform removal, s exemplified by the following quote:

'Capabilities? There are actually no special capabilities required from the dentist. … One should be able to judge it visually and tactile, hold the bur correctly, detain and drill the cavity up correctly.' (Dentist No.1)

(3) Beliefs about consequences

Most dentists believed that SE prevented endodontic treatment. Nine out of ten also believed that SE does not lead to a progression of the lesion:

'Oh, the benefits. Yes, the advantage I see is frankly the attempt of avoiding a pulp opening and endodontic treatment and that works quite well. And then you just have a vital tooth without endodontic treatment, and I see the advantage in this.' (Dentist No. 8)

(4) Coping

Half of the interviewees mentioned the possible failure of a therapy and their coping with it:

'So, the advantages of SE would of course be that we are able to keep the tooth vital, which we had otherwise to treat with a root-canal treatment. So, we would not have to drill the pulp. (…) The tooth stays vital and its survival in the mouth is longer. When I have of course the disadvantage some things might go wrong, that the patient has complications and I have to perform a root-canal treatment in the end.' (Dentist No.4)

'It influences my treatment in so far as that I would do more follow ups, and probably do more x-rays in the process. So not weekly one, but after ½ year, 1 year, 2 years I would do an x-ray, in the sense of a bitewing. To keep an eye on it.' (Dentist No.5)

(5) Intentions

In this domain, most of the comments were grouped under treatment goals. Dentists mentioned the improvement of oral health and avoiding further treatment and complications as the main reason for choosing a treatment. Within the construct of intrinsic motivation several dentists mentioned that they aimed to apply the best possible treatment for each individual case.

'I try of course always to keep the pulp vital, that is the primary target'. (Dentist No.10)

'In my opinion one tries to find the best possible decision for the individual case.' (Dentist No.7)

(6) Environmental context and resources

Environmental context and resources was one of the less frequently mentioned domains. None of the participants stated that economic factors were relevant for their decision towards carious tissue removal. Material seems to have an influence though, as all dentists mentioned good lighting and magnifying glasses to be helpful. The influence of factors like insurance rules and health policies were not mentioned by the interviewees.

'I would also always say the good lighting is advantageous and a magnification. One has to have a good view…. (…) and you have to have a good view and magnification.' (Dentist No. 5)

(7) Social Influences

The comments in this domain pertained to the interests of patients, and the role of patients and colleagues. Some dentists anticipated that patients wanted only one, short, painless treatment. Some believed that if the patient was informed about SE, he/she would prefer this. Most agreed that patients wanted to avoid endodontic treatment. Supportive colleagues were found helpful for performing SE.

'Most of the patients want to avoid endodontic treatment. Of course, endodontic treatment is a keyword that is negative. But that is what the patients care for, and there is an interest to avoid it in the first place.' (Dentist No. 10)

'No patient wants you to excavate selectively, but if you explain the situation to them, no one wants you to excavate fully.' (Dentist No.3)

(8) Emotion

The domain Emotions contained comments about stress, anxiety and fear. Eight dentists stated not to worry about their treatment or the patient, being sure to find the best possible solution for every individual case.

'I don't worry. It's a manageable problem. And in case of emergency one still has the root canal treatment left as an option.' (Dentist No.9)

From these data, four barriers were identified:

1 The most often stated barrier was the lack of guidelines on SE. Dentists stated that they were willing to follow those guidelines to implement SE in their daily routine.
2 The dentists also mentioned discrepancies between the knowledge they learned at university and new scientific findings on SE.
3 Most interviewees mentioned the lack of experience with SE and fear of endodontic complications after SE.
4 Most dentists lacked routine in applying SE.

Also, four facilitators were identified:

1 Understanding the biological foundations for SE.
2 Knowing that SE was evidence-based and proven for protecting the integrity of the pulp and avoiding endodontic treatment.
3 The existence of a precise application guide and the availability of reliable criteria for determining the endpoint of SE.
4 Involving patients in a shared decision making.

Table 2
Responses to different questions in different intervention groups. P-values indicate the level of significance for differences in the response distributions between baseline (BL) and post-intervention (PI) within each group. Post-intervention differences between groups are indicated by asterisks (*) at each question ($p < 0.01$).

Question	Scale	Group "Guideline"				p-value	Group "Tool"				p-value
		BL	BL %	PI	PI %		BL	BL %	PI	PI %	
1. Dentin Hardness*	hard	115	46.6%	43	17%	< 0.001	103	46.6%	66	28.8%	< 0.001
	leathery	111	44.9%	159	62.8%		102	46.2%	116	50.7%	
	soft	14	5.7%	26	10.3%		11	4.9%	11	4.8%	
	Does not matter	7	2.8%	25	9.9%		5	2.3%	36	15.7%	
2. Dentin Color	Not discolored	16	6.5%	4	1.6%	< 0.001	13	5.9%	11	4.9%	< 0.001
	discolored	73	29.4%	76	30.9%		65	29.6%	59	26.1%	
	Very discolored	10	4.0%	12	4.9%		8	3.6%	16	7.1%	
	Does not matter	149	60.1%	153	62.2%		134	60.9%	140	61.9%	
3. Dentin Moisture	dry	151	61.2%	119	47.8%	< 0.001	138	63%	106	48.2%	< 0.001
	moist	45	18.2%	67	26.9%		45	20.6%	54	24.5%	
	very moist	3	1.2%	4	1.6%		2	0.9%	3	1.4%	
	Does not matter	48	19.4%	59	23.7%		34	15.5%	57	25.9%	
4. Removal differs depending on area of tooth	Strongly agree	163	65.5%	178	70.1%	< 0.001	163	73.1%	140	60.6%	< 0.001
	agree	56	22.5%	58	22.8%		39	17.5%	56	24.3%	
	Partly agree	16	6.4%	10	3.9%		17	7.6%	19	8.2%	
	disagree	10	4.0%	4	1.6%		4	1.8%	9	3.9%	
	Strongly disagree	4	1.6%	4	1.6%		0	0.0%	7	3.0%	
5. Non-selective removal prevents lesion progress*	Strongly agree	27	10.8%	10	3.8%	< 0.001	14	6.3%	13	5.5%	< 0.001
	agree	52	20.9%	27	10.3%		45	20.4%	43	18.2%	
	Partly agree	80	32.1%	50	19.2%		74	33.5%	70	29.5%	
	disagree	45	18.1%	68	26.1%		50	22.6%	59	24.9%	
	Strongly disagree	45	18.1%	106	40.6%		38	17.2%	52	21.9%	
6. Sealing bacteria inactivates them*	Strongly agree	79	30.5%	136	52.7%	< 0.001	76	31.9%	83	35.0%	< 0.001
	agree	66	25.5%	68	26.3%		81	34.0%	81	34.2%	
	Partly agree	61	23.6%	34	13.2%		37	15.6%	42	17.7%	
	disagree	34	13.1%	12	4.7%		28	11.8%	23	9.7%	
	Strongly disagree	19	7.3%	8	3.1%		16	6.7%	8	3.4%	
7. Scientific reports impact on behavior	Strongly agree	134	51.5%	140	53.6%	< 0.01	123	51.7%	133	55.9%	0 < 0.01
	agree	78	30.0%	78	29.9%		73	30.7%	67	28.1%	
	Partly agree	41	15.8%	38	14.6%		36	15.1%	33	13.9%	
	disagree	5	1.9%	3	1.1%		6	2.5%	5	2.1%	
	Strongly disagree	2	0.8%	2	0.8%		0	0.0%	0	0.0%	
8. Lacking reliable endpoint hampers SE*	Strongly agree	26	10.0%	11	4.2%	< 0.001	22	9.3%	133	56.4%	< 0.001
	agree	59	22.7%	32	12.3%		48	20.2%	70	29.7%	
	Partly agree	61	23.5%	49	18.8%		47	19.8%	22	9.3%	
	disagree	51	19.6%	69	26.4%		67	28.3%	7	2.9%	
	Strongly disagree	63	24.2%	100	38.3%		53	22.4%	4	1.7%	

These barriers and facilitators were used to develop the described interventions (as described above).

3.2. Behavioral change simulation experiment

The total number of responders for our experiment was n = 504 (Fig. 1), the response rate was 25%. The demographic and further characteristics of the responders in both groups were largely in line with those of the target population, and did not differ significantly between intervention groups (see Appendix Material 4).

Baseline answers for most questions did not significantly differ between groups (Table 2). For our primary outcome, at baseline, 46.6% of the dentists would leave only hard dentin behind, 45.5% stated to excavate until the dentin was leathery, 5.5% would leave soft dentin behind, 2.4% stated that hardness did not matter to them.

There were significant differences in most responses post-intervention compared with baseline (Table 2). Our primary outcome was significantly different post-intervention compared with baseline in both interventions ($p < 0.001$), with 29.6% and 17.8% of dentists being less invasive (i.e. leaving softer dentin) post-intervention than at baseline, respectively. Dentists in the intervention group 'Guideline' were significantly more positive towards sealing bacteria (i.e. showed more knowledge) than dentists in the 'Tool' group. Vice versa, in the 'Tool' group, significantly more dentists said that a reliable endpoint was not a problem for them post-intervention than in the 'Guideline' group.

Differences in the primary outcome between groups were further analyzed via multinomial ordinary regression, accounting for possible covariate imbalances between groups (these were limited, though). Only age significantly predicted post-intervention behavior, while neither intervention nor year of exam nor baseline behavior significantly predicted post-intervention behavior. Details on this analysis can be found in the Appendix Material 5.

4. Discussion

Dentists' behavior for managing deep carious lesions has been investigated by a range of observational studies before, using mainly survey methodology [9,32]. Such studies are useful to measure how often, for example, different carious tissue strategies are employed and, generally, to detect if dentists follow evidence-based advice in their treatment of deep lesions. They are, however, unable to truly understand underlying factors for the displayed behavior and only of limited use in developing interventions to target behavior change [34]. The present study used qualitative one-to-one-interviews with German dentists, underlined by the TDF both to conduct the interviews and analyze the data in order to understand the barriers and facilitators for performing SE. We then used the interview data to derive two interventions and tested them on a representative sample of German dental practitioners via a behavior change simulation experiment. We identified a range of barriers and enablers and showed that both interventions had a significant impact on the simulated behavior. Dentists were less invasive (leaving soft dentin more often) after than before the interventions. Notably, in the group 'Guideline', dentists' knowledge was changed in parallel to their simulated behavior, while in group 'Tool',

this was not the case.

Our study builds on a theoretically grounded approach [16]. Behavior change interventions are more effective if based on an established theory [35–37]. A range of behavior change theories are available, assuming – for example – that behavior intention, past behavior or self-efficacy are the main predictors of behavior (change) [11,37]. However, none of the theories provide a comprehensive understanding of how behavior change can be facilitated [37]. In the present study, the TDF was used. The TDF is not a theory per se, but a combined framework, lending from several theories, which allows the development of tailored interventions in a comprehensive, systematic and reproducible manner [38–40]. The use of the TDF has been found to result "in greater breadth of potential explanations" compared with the use of "only a single theoretical model" [14,34]. The TDF can be linked with the BCW and the BCTTv1, matching Behavior Change Techniques to identified barriers and facilitators. The resulting interventions are therefore empirically based, and their development can be reviewed and compared across studies [13,21].

Our findings demonstrated the potential change in simulated behavior by different interventions, and possible underlying reasons for this change. The intervention group 'Guideline' received theoretical information about the disease caries, the biological fundamentals of carious tissue removal, and evidence-based recommendations about the treatment of deep lesions, based on a statement from a national dental association. This likely led to (1) a change in understanding and (2) a feeling of support from peers and authorities. Participants of the intervention group 'Tool' were asked to imagine them having a tool to reliably determine the endpoint of SE. This group did not show changes in knowledge but found the issue of removal endpoint to no longer hamper the adoption of SE. Both interventions have potential for application in the real world. For example, improving dentists' knowledge is possible. Continuous professional development (CPD) for German dentists does currently not involve mandatory updates in cariology, while these could be helpful based on the findings of our study. Also, pre-graduate dental education does not seem to be fully in line with current evidence and given the identified role of knowledge gained at university, there seems leverage for change here as well. Notably, though, age was a predictor of post-intervention behavior; older dentists were more likely to leave only hard dentin (year of exam was not a predictor, but we assume this to have been due to loading onto the factor age). The wider application of existing self-limiting carious tissue removal techniques like polymer burs, which come with an inherent defined endpoint, should be considered as well. Future research should test the efficacy of such burs etc., and address the barriers of applying them.

This study has a number of strengths. First, qualitative and quantitative methods were combined, strengthening the robustness of our findings by method triangulation. Developing interventions based on a theoretically-grounded analysis of qualitative data improves their reproducibility and effectivity. We also used the BCTTv1, a comprehensive choice of behavior change techniques [41], which increases the likelihood that an intervention matches the specifically targeted behavioral problem and is effective. Second, while the interventions we tested seemed to have a positive effect on potential behavior change, they were not only targeting specific behavior, but also considered the APEASE criteria [17]. Notably, a "tool", given its potential cost, is likely to come with lower cost-effectiveness and, given it needed to be bought, may also be less equitable than a "guideline". Third, we used a randomized design for testing the simulated behavior change, reducing selection, performance and detection bias.

The study also has a number of limitations. First, the selection of the interviewees followed a purposive or snowball sampling, and while we took care in sampling dentists of different age, sexes and backgrounds, these were not representative. Thus, certain barriers and enablers may have been missed. Second, the response to the behavior change experiment was, at 25%, relatively low, but similar to previous surveys in the field [15,41,42]. While the comparison of our sample against the national body of dentists found the sample to be rather representative (respondents were only minimally older than the national average of dentists), we cannot exclude selection bias (also as we had no chance to follow-up non-responders to compare them against the responders). Furthermore, this study is a cross-sectional study and there are potential limitations from participants receiving the pre- and post-questionnaires at the same time, as discussed. Another limitation may be the unclear transferability of our interventions into 'real-life'. However, previous studies found that simulation experiments can predict certain real-life outcomes and are useful in designing and selecting behavior change interventions for real-life use [43].

5. Conclusions

Understanding the barriers and facilitators for applying SE was useful to systematically develop theoretically grounded behavior change interventions. These were efficacious in the performed behavior change simulation experiment. The potential for implementation of guidelines combined with mandatory cariology updates as CPD-requirement seems to be a promising solution and a way forward to achieve successful adaptation and optimal implementation of SE.

Conflict of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jdent.2018.12.010.

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