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Review

Spreading the reduction of fear: A narrative review of generalization of extinction learning in human fear conditioning

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ABSTRACT

Extinction learning refers to a reduction in fear to a conditioned stimulus (CS) that previously signaled a threat, but now occurs without the expected threat. This mechanism is core to exposure-based treatments for anxiety-related disorders. Enhancing the generalization of extinction learning is crucial for improving treatment outcomes, as it helps reduce fear across a range of generalization stimuli (GSs) resembling the original fear-evoking CS. This narrative review identifies and covers three generalization of extinction learning models: 1) generalization of CS extinction learning, examining how extinction learning to the CS generalizes to novel GSs, 2) generalization of GS extinction learning, assessing how extinction learning to a GS generalizes to other novel GSs or the original CS, and 3) generalization of multiple stimuli extinction learning, where extinction learning involves multiple GSs (and sometimes the CS) and its effect on other novel stimuli. While extinction learning to the CS effectively generalizes to other stimuli, extinction learning to a GS or multiple GSs showed limited generalization to other novel GSs or the original CS. Since real-life exposure-based treatment rarely reproduces the CS, extinction learning involving only the GS(s) may better reflect clinical practice; poor generalization of GS(s) extinction learning may constitute another pathway of return of fear. This review also highlights various factors that influence generalization of extinction learning and call for future research to develop strategies for improving these processes, which can help inform exposure-based treatments.

1. Introduction

Exposure-based treatment is widely regarded as an effective treatment for anxiety-related disorders (Bandelow et al., 2015; Watts, Turnell, Kladnitski, Newby, & Andrews, 2015). A part of exposure-based treatment involves repeatedly exposing individuals to feared stimuli or situations without the anticipated threat. For example, a person with a dog phobia might be repeatedly exposed to dogs in the absence of an expected dog attack. Through these sessions, maladaptive threat beliefs about the feared stimuli are gradually disconfirmed. However, recent research indicates that exposure-based treatment only yields moderate reductions in anxiety symptoms (Carpenter et al., 2018), and relapse rates after successful treatment remain high (Boschen, Neumann, & Waters, 2009; Craske & Mystkowski, 2006). Thus, there is a need for strategies to enhance treatment effectiveness and sustain outcomes over time.

Exposure sessions can be modelled in a highly controlled fear conditioning framework via extinction learning. Before extinction learning occurs, a previously neutral conditioned stimulus (CS+) is repeatedly paired with an aversive unconditioned stimulus (US). After repeated CS – US pairings, the CS+ elicits conditioned fear, modelling the development of fear responses in anxiety-related disorders. During extinction training, the CS+ is repeatedly presented without the US, parallel to repeated exposure to feared stimuli in treatment. Extinction learning, however, does not erase the CS – US association (i.e., the fear memory). Instead, it creates a new CS - no US association (i.e., the extinction memory), which inhibits the retrieval of the fear memory when the extinguished CS+ is presented (Bouton, 1993, 2004). Under certain conditions, the retrieval of the fear memory is favored over the extinction memory, leading to a return of fear. These conditions include the mere passage of time (spontaneous recovery; Rescorla, 2004), through unsignaled US presentations (reinstatement; Haaker, Golkar, Hermans, & Lonsdorf, 2014), or when the CS+ is presented in a different context than where extinction learning occurred (contextual renewal; Bouton, 2004). To address these challenges, various strategies, such as optimizing extinction learning per se, enhancing extinction memory

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retrieval, or reducing context dependency of the extinction memory, have been explored to help enhancing treatment outcomes and reducing relapse. There are some excellent reviews that have discussed these strategies in detail (e.g., Craske, Treanor, Conway, Zbozinek, & Vervliet, 2014; Pittig, van den Berg, & Vervliet, 2016; Quintero, López, Vadillo, & Morís, 2024; Sewart & Craske, 2020; Vervliet, Craske, & Hermans, 2013; Weisman & Rodebaugh, 2018). Yet, one critical strategy, generalization of extinction learning, remains underexplored in the literature. This review examines this process, proposing that it is not merely a strategy to enhance treatment outcome but a process that closely resembles real-life exposure-based treatment.

Generalization of extinction learning refers to the spread of inhibitory responses learned to the extinction stimulus, ideally inhibiting generalized fear to similar stimuli. Effective generalization of extinction learning is critical in clinical contexts where individuals often encounter a variety of fear-evoking stimuli or situations that may differ from those directly addressed in exposure-based treatments. Therefore, a key target for advancing the effectiveness of exposure-based treatments is to promote robust generalization of extinction learning. To this end, it is of clinical importance to evaluate the effectiveness of the generalization of extinction learning, examine its mechanisms, and identify factors that enhance or impede this process. This review identifies three laboratory models examining the various forms of generalization of extinction learning, including the *generalization of CS extinction learning model*, the *generalization of GS extinction learning model*, and the *generalization of multiple stimuli extinction learning model.* The most typically examined model involves the *generalization of CS extinction learning* (see Fig. 1). In this model, the CS+ is presented in the absence of an US during extinction training. In a following post-extinction test, it is of typical interest to examine whether such learning generalizes to other novel generalization stimuli (GSs) resembling the CS+ (e.g., Klein et al., 2024; Vervliet, Vansteenwegen, & Eelen, 2004; Wong & Lovibond, 2020). This model evaluates how well inhibitory responses to the original stimulus of fear acquisition generalize to other similar stimuli.

However, the exact stimulus of fear acquisition is most likely impossible to reproduce for treatment use. For example, in the treatment of post-traumatic stress disorder in child abused victims, recreating the exact perpetrator is not feasible. Instead, stimuli resembling the original stimulus of fear acquisition (e.g., other authority figures) are typically used in exposure-based treatment. This scenario corresponds to *generalization of GS extinction learning* in fear conditioning studies (see Fig. 1), where a GS is presented during extinction training rather than the CS+ itself (e.g., Gerdes, Fraunfelter, & Alpers, 2020; Vervliet & Geens, 2014; Vervliet, Vansteenwegen, Baeyens, Hermans, & Eelen, 2005). In this model, generalized fear to the GS initially occurs but diminishes across extinction training trials. This closely models how stimuli that resemble the stimulus of fear acquisition are presented over multiple exposure sessions in exposure-based treatments. In one variant of this model, the stimulus of fear acquisition (CS+) is presented in a post-extinction test, providing a testbed for examining how effectively extinction learning to a GS transfers to the original stimulus of fear acquisition (e.g., Barry, Vervliet, & Hermans, 2017; Crombie et al., 2023). Another variant of this model presents novel GSs resembling the CS+ in the post-extinction test, examining how extinction learning to one GS generalizes to other novel GSs. This variant parallels to presenting a fear-evoking stimulus across exposure sessions, and how effective extinction learning to this stimulus inhibits fear to other novel, fear-evoking stimuli, arguably more in line with real-life treatment.

Another generalization of extinction learning model involves the presentation of multiple fear-evoking stimuli during extinction training (e.g., Kroes, Dunsmoor, Lin, Evans, & Phelps, 2017; Waters, Kershaw, & Lipp, 2018; Zbozinek & Craske, 2018). This model, hereafter *generalization of multiple stimuli extinction learning* (Fig. 1), typically involves presenting multiple GSs resembling the CS+ during extinction training and examines whether extinction learning to these stimuli would generalize to other novel GSs or to the original CS+.

In each of these generalization of extinction learning models, the generalization of extinction learning are typically examined through perceptual generalization and conceptual generalization. Perceptual generalization involves GSs that are physically similar to the CS+. On a theoretical perspective, each stimulus consists of numerous hypothetical elements, and stimuli that are more similar share more elements (Blough, 1975; Mclaren & Mackintosh, 2002). After CS – US pairings, each hypothetical element of the CS+ acquires excitatory strength which evokes conditioned fear. Likewise, elements in the CS+ acquire inhibitory strength after CS extinction learning, which inhibits conditioned fear. According to these elemental accounts, *generalization of CS extinction learning* is thought to be effective as all individual elements of the CS+ acquire inhibitory strength after successful CS extinction learning. GSs that share common elements with the extinguished CS+

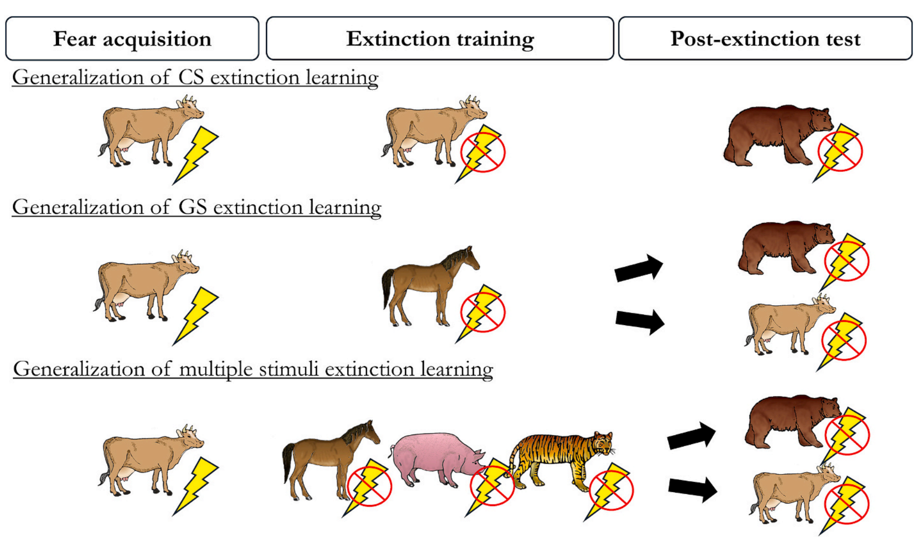

Fig. 1. The three reviewed models of generalization of extinction learning. The model in the top panel depicts *generalization of CS extinction learning*, which involves a CS+ during extinction training, and a novel GS in post-extinction test. The model in the middle panel depicts *generalization of GS extinction learning*, which involves a GS during extinction training, and another novel GS or the CS+ in post-extinction test. The model in the bottom panel depicts *generalization of multiple stimuli extinction learning*, which involves multiple GS (and sometimes the CS+) during extinction training, and another novel GS or the CS+ in post-extinction test. The stimuli were provided by Rossion and Pourtois (2004).

will also acquire inhibitory strength, while the unique elements in these GSs have never acquired any excitatory strength. Therefore, the GSs presented after CS extinction learning evoke limited to no conditioned fear, reflecting strong *generalization of CS extinction learning*. On the other hand, *generalization of GS extinction learning* to either a CS+ or a novel GS is thought to be less effective. After GS extinction learning, the unique elements of the CS+ (i.e., elements not shared with the extinction GS) still retain excitatory strength, thus still capable to evoke conditioned fear. Likewise, the novel GS in post-extinction test consists of elements shared with the CS+ but not with the extinction GS, thus retaining excitatory strength and evoke conditioned fear. These elemental models suggest that presenting multiple GSs during extinction training (*generalization of multiple stimuli extinction learning*) may enhance the generalization of extinction learning. This is because presenting multiple GSs increases the numbers of elements shared with the CS+ to acquire inhibitory strength during extinction training, thus decreasing the numbers of unique elements of the CS+ that remain excitatory strength after extinction training. Perceptual generalization is typically examined as researchers have controlled over shared perceptual features between stimuli, thus allowing precise examination whether the degree of generalization of extinction learning is a function of perceptual similarity.

However, fear generalization in real-life often involves complex stimuli with multiple dimensions instead of mere perceptual similarity (Dunsmoor & Murphy, 2015). Conceptual fear generalization can account for this complexity as it involves generalization beyond perceptual similarity and operates via a higher-order cognitive process. In a fear conditioning model, this refers to generalized responding to stimuli that are conceptually similar to the CS+ (Dunsmoor & Murphy, 2015; Dymond, Dunsmoor, Vervliet, Roche, & Hermans, 2015). For instance, generalized responses to novel stimuli that belong to the same category of the CS+ (i.e., categorical generalization), or to novel stimuli that are semantically related to the CS+ (i.e., semantic generalization). Recent evidence points to the similarity between conceptual generalization and inductive reasoning (e.g., Dunsmoor, Martin, & LaBar, 2012; Dymond et al., 2011; Wong & Lovibond (2021)), as both involve inferring the knowledge learnt to the CS+ (in fear conditioning) or to the target premise (in inductive reasoning) to novel stimuli. Learning that a CS+ signals an aversive shock and then generalizing this threat expectancy to similar stimuli (in fear conditioning) is similar to learning that a cow has a specific property and inferring that other mammals share this property (in inductive reasoning) – both involve extending learnt information to related concepts. Theoretically, all generalization of extinction learning models (*generalization of CS extinction learning*, *generalization of GS extinction learning*, and *generalization of multiple stimuli extinction learning*) should show (conceptual) generalization of extinction learning if the CS+, stimuli presented during extinction training and post-extinction test are conceptually related to each other. Preliminary evidence has shown that factors that affect the strength of inductive inference, such as typicality or diversity of the training stimuli, similarly affect the strength of fear generalization (Dunsmoor & Murphy, 2014; Fan et al., 2022; Wong & Beckers, 2021). Similarly, it is expected these factors will also affect generalization of extinction learning in a similar way.

In sum, this narrative review aims to elucidate the effectiveness of various forms of generalization of extinction learning and their clinical relevance. To this end, the aim of this review is threefold:

1) Based on existing evidence, this review evaluates the effectiveness of perceptual and conceptual generalization within the three generalization of extinction learning models: *Generalization of CS extinction learning model*, *Generalization of GS extinction learning model*, and *Generalization of multiple stimuli extinction learning model*.
2) This review examines factors that enhance or impair the generalization of extinction learning, including clinical anxiety symptoms, subclinical anxiety traits, cognitive factors, neurobehavioral factors and biobehavioral factors.
3) This review outlines the theoretical mechanisms underlying the findings and their clinical relevance. Drawing on these findings, future directions to optimize their clinical application are proposed.

This narrative review employed a systematic search strategy to identify all available evidence on the generalization of extinction learning, with the detailed methodology provided in the Supplementary Materials. From this search, 39 studies were included in this review, with their experimental parameters summarized in Table 1.

2. Models of generalization of extinction learning

2.1. Generalization of GS extinction learning

Vervliet et al. (2004) was one of the earliest human fear conditioning studies to examine whether CS extinction learning effectively generalizes to other perceptually similar GSs. Participants first acquired stronger fear responding to a CS+ compared to a safety CS- (that signaled the absence of a US). After successful extinction learning to the CS+, participants showed no differential responding to a threat-related GS (that perceptually resembles CS+) and a safety-related GS (that perceptually resembles the CS-), as indexed by both threat expectancy ratings and skin conductance responses. This pattern suggests that CS extinction learning effectively generalizes to other perceptually similar GSs. More recent studies also showed limited generalized fear to GSs in the post-extinction test after CS extinction learning (Glenn et al., 2021; Goldfarb, Blow, Dunsmoor, & Phelps, 2021; Shiban, Reichenberger, Neumann, & Mühlberger, 2015; Vervliet et al., 2004; Waters, Ryan, Luck, Craske, & Lipp, 2023; Zbozinek & Craske, 2018), further supporting that CS extinction learning does generalize strongly to other GSs. Interestingly, Glenn et al. (2021) only found great *generalization of CS extinction learning* when the US was a social threat (i.e., a facial stimulus with fearful expression coupled with a loud scream) but not when the US was a physical threat (an aversive sound). However, despite CS extinction learning greatly generalizes to other GSs, it is bounded by perceptual similarities between the CS+ (in extinction training) and GS (in post-extinction test). In a post-extinction test, GSs that were perceptually more different from the CS+ evoke more generalized fear compared to GSs that were perceptually more similar to the CS+ (Waters et al., 2023). Other studies (Gazendam et al., 2020; Waters, Ryan, Luck, Craske, & Lipp, 2021) also showed similar patterns to a GS perceptually different from the CS+. Interestingly, preliminary evidence suggests that *generalization of CS extinction learning* also occurs across different sensory modalities (Gerdes et al., 2020). After acquiring and subsequently extinguishing fear to an image of a typewriter (CS+), participants showed limited to no generalized fear to an audio sound of a typewriter (GS).

In contrast, other studies showed that participants still exhibited substantial generalized fear to the GSs after CS extinction learning (Glenn et al., 2021; Lange et al., 2019; Michalska et al., 2016; Shi et al., 2018; Waters et al., 2018), suggesting that CS extinction learning does not always generalize strongly to other stimuli. Interestingly, four of these five studies used a multiple-day paradigm (Glenn et al., 2021; Lange et al., 2019; Michalska et al., 2016; Shi et al., 2018), in which extinction training and post-extinction test were assessed in separate days. This weak *generalization of CS extinction learning* could be attributed to weak extinction retention via spontaneous recovery (Rescorla, 2004), leading to the recovery of generalized fear in post-extinction test. In addition, Klein, Shner, Ginat-Frolich, Vervliet, and Shechner (2020) examined whether CS extinction learning could generalize to safety behaviors. Safety behaviors refer to within-situation avoidance behaviors that reduce the chance of the occurrence of an expected threat, which is typically operationalized as a response to the CS+ that prevents US onset in a fear conditioning framework (Krypotos, Vervliet, &

Table 1
Data extracted from the reviewed studies. CS indicates conditioned stimulus; US indicates unconditioned stimulus; GS indicates generalization stimulus; in the "Models" column, CS indicates *generalization of CS extinction learning model*, GS indicates *generalization of GS extinction learning model*, MS indicates *generalization of multiple stimuli extinction learning model.*

Study	Sample	Age (SD/range)	Sex	CS	US	Stimuli presented in extinction training	Stimuli presented in post-extinction test	Model (s)	Extinction training and post-extinction test assessed on the same day?	Manipulation between extinction training and post-extinction test
Barry, Griffith, Vervliet, and Hermans (2016)	$N = 48$	21.20(3.20)	33♀,15♂	Fribbles	Electric shock	GSs	ABA group: CSs ABB group: Extinction GS ABC group: Novel GSs	GS	Yes	NA
Barry, Vervliet, and Hermans (2016)	$N = 25$	23.0(2.80)	18♀,7♂	Combination of geometric shapes that resemble animals and insects	Electric shock	GS	Novel GSs	GS	Yes	NA
Barry et al. (2017)	$N = 48$	20.00(3.00)	40♀,8♂	Fribbles	Electric shock	GSs	Novel GSs	GS	Yes	NA
Crombie et al. (2023)	Control: $n = 20$ Exercise: $n = 20$	Control: 34.55 (10.21) Exercise: 32.05(9.52)	Control: 20♀, 0 ♂ Exercise: 20♀, 0 ♂	Unique images from either "animal" or "tool" category	Electric shock	Novel GSs	CSs & Novel GSs	MS	Day1: Acquisition Day2: Extinction training Day 3: Extinction recall	Spontaneous recovery & reinstatement
Endhoven, Krypotos, Mertens, and Engelhard (2024)	$N = 55$	23.83(3.48)	40♀,15♂	Geometric shapes	Scream	CSs	CSs and novel GSs	CS	Yes	NA
Gazendam et al. (2020)	$N = 924$	24.61(1.81)	481♀,443♂	Facial stimuli	Electric shock	CSs	CSs and novel GSs	CS	Yes	Reinstatement for the CSs No manipulation for the novel GSs
Gerdes et al. (2020)	Unimodal: $n = 21$ Crossmodal: $n = 20$	21.56(2.74)	29♀,12♂	Black and white drawing	Electric shock	Unimodal: CSs Crossmodal: GSs	CSs and extinction GSs	CS GS	Yes	NA
Glenn et al. (2021)	Youth group: $n = 16$ Adult group: $n = 20$	Youth group: 14.1(1.7) Adult group: 25.7(4.9)	Youth group: 10♀,6♂ Adult group: 12♀,8♂	Colored bells or facial stimuli	Sound	CSs	CSs and novel GSs	CS	Day 1: Acquisition and Extinction training Day 22: Extinction recall	Spontaneous recovery
Goldfarb et al. (2021)	Compound: $n = 48$ Separate: $n = 48$	Compound: 23(4.01) Separate: 22.25(4.14)	Compound: 26♀,22♂ Separate: 30♀,18♂	Geometric shapes and tones	Electric shock	Elemental CSs	Elemental CSs and Compound CSs	CS GS	Yes	NA
Hagedorn, Wolf, and Merz (2021)	$N = 60$	24.5(3.8)	30♀, 30♂	Geometric shapes	Electric shock	CSs and GSs	CSs and novel GSs	MS	Day 1: Acquisition Day 2: Extinction training	Spontaneous recovery & reinstatement

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Table 1 (*continued*)

Study	Sample	Age (SD/ range)	Sex	CS	US	Stimuli presented in extinction training	Stimuli presented in post-extinction test	Model (s)	Extinction training and post-extinction test assessed on the same day?	Manipulation between extinction training and post-extinction test
									Day 3: Extinction recall	
Hagedorn, Wolf, and Merz (2022)	$N = 60$	23.9(4.1)	30♀, 30♂	Geometric shapes	Electric shock	CSs and GSs	CSs and novel GSs	MS	Day 1: Acquisition Day 2: Extinction training Day 3: Extinction recall	Spontaneous recovery & reinstatement
Hennings, Bibb, Lewis-Peacock, and Dunsmoor (2021)	Experiment 1: $N = 21$ Experiment 2: $N = 21$	Experiment 1: 18–45 Experiment 2: 18–45	Experiment 1: 12♀,9♂ Experiment 2: 14♀,7♂	Images of animals, food, and tools	Electric shock	GSs	Novel GSs	MS	Day 1: Acquisition and Extinction training Day 2: Extinction recall	Spontaneous recovery
Klein et al. (2020)	Youth: $n = 34$ Adults: $n = 45$	Youth: 15.99 (13–17) Adults: 24.57 (19–46)	Youth: 17♀,17♂ Adults: 31♀,14♂	Colored bells	Sound	CSs	CSs and novel GSs	CS	Yes	NA
Klein, Ginat-Frolich, Barry, and Shechner (2021)	$N = 65$	24.95(4.04)	52♀,13♂	Facial stimuli	Woman screaming	CSs	CSs and novel GSs	CS	Day 1: Acquisition and Extinction training Day4: Extinction recall	Spontaneous recovery
Klein, Abend, Shmuel, and Shechner (2022)	$N = 133$	10.67(1.96)	67♀, 66♂	Images of different colored bells	Sound	CSs	CSs and novel GSs	CS	Day 1: Acquisition & extinction training Day 8: Extinction recall	Spontaneous recovery
Klein et al. (2024)	Anxious: $n = 28$ Non-anxious: $n = 33$	Anxious: 11.18(2.02) Non-anxious: 11.62(2.70)	Anxious: 16♀, 11♂ Non-anxious: 16♀, 17♂	Images of different colored bells	Sound	CSs	CSs and novel GSs	CS	Day 1: Acquisition & extinction training Day 8: Extinction recall	Spontaneous recovery
Kroes et al. (2017)	Reminder group: $n = 18$ No-reminder group: $n = 20$	Reminder group: 21.17(2.09) No-reminder group: 22.90(2.55)	Reminder group: 11♀,7♂ No-reminder group: 10♀,10♂	Images of birds and fish	Electric shock	GSs	Novel GSs	MS	Day 1: Acquisition Day 2: Extinction training Day 3: Extinction recall	Reinstatement
Lange et al. (2019)	Spider phobia: $n = 46$ Healthy control: $n = 48$	Spider phobia: 20.57(2.37) Healthy	Spider phobia: 42♀,4♂ Healthy	Geometric shapes	Electric shock	CSs	CSs and novel GSs	CS	Day 1: Acquisition Day2: Extinction training	Spontaneous recovery

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Table 1 (*continued*)

Study	Sample	Age (SD/ range)	Sex	CS	US	Stimuli presented in extinction training	Stimuli presented in post-extinction test	Model (s)	Extinction training and post-extinction test assessed on the same day?	Manipulation between extinction training and post-extinction test
		control: 20.94(1.84)	control: 39♀,9♂						Day 3: Extinction recall	
Michalska et al. (2016)	$N = 48$	5–10	27♀,21♂	Colored bells	Sound	CSs	CSs and novel GSs	CS	Day1: Acquisition and Extinction training Day25: Extinction recall	Spontaneous recovery
Michalska et al. (2019)	$N = 59$	13.35(0.63)	26♀,33♂	Colored bells	Sound	CSs	CSs and novel GSs	CS	Day 1: Acquisition and Extinction training Day 22: Extinction recall	Spontaneous recovery
Meir Drexler, Merz, Lissek, Tegenthoff, & Wolf (2019)	$N = 75$	25.43(4.54)	0♀,75♂	Geometric shapes	Electric shock	CSs (plus US reactivation prior to extinction training)	CSs and novel GSs	CS	Day 1: Acquisition Day 2: Memory reactivation Day 3: Extinction training and extinction recall	Reinstatement
Scheveneels, Boddez, Bennett, and Hermans (2017)	Typical group: $n = 35$ Atypical group: $n = 34$	21.30(4.18)	83♀,19♂	Fribbles	Electric shock	GSs	Novel GSs	GS	Yes	NA
Scheveneels, Boddez, Vervliet, and Hermans (2019)	$N = 64$	22.31(6.04)	53♀,11♂	Facial stimuli	Electric shock	CSs and GSs	CSs and a novel GS	MS	Day 1: Acquisition Day 2: Extinction training Day 3: Extinction recall	Spontaneous recovery
Shechner et al. (2018)	Behavioral inhibition group: $n = 27$ Non-behavioral inhibition group: $n = 40$	Behavioral inhibition group: 20.24 (11.21) Non-behavioral inhibition group: 20.74 (11.30)	Behavioral inhibition group: 12♀,15♂ Non-behavioral inhibition group: 20♀,20♂	Facial stimuli	Woman screaming	CSs	CSs and novel GSs	CS	Day 1: Acquisition and Extinction training Day 22: Extinction recall	Spontaneous recovery
Shi et al. (2018)	$N = 91$	18–30	0♀,91♂	Colored geometric shapes	Electric shock	CSs	Novel GS	CS	Day 1: Acquisition Day 2: Extinction training Day 3:	Reinstatement

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Table 1 (*continued*)

Study	Sample	Age (SD/range)	Sex	CS	US	Stimuli presented in extinction training	Stimuli presented in post-extinction test	Model (s)	Extinction training and post-extinction test assessed on the same day?	Manipulation between extinction training and post-extinction test
									Extinction recall	
Shiban et al. (2015)	$N = 40$	22.00(5.22)	37♀,3♂	Avatar	Air blast and scream	CSs	CSs and novel GSs	CS	Day1: Acquisition and Extinction training Day2: Extinction recall	Spontaneous recovery
Soeter and Kindt (2012)	$N = 40$	20.7(1.9)	30♀,10♂	Pictures and semantic stimuli	Electric shock	CSs	CSs & novel GSs	CS	Day1: Acquisition Day2: CS reminder Day3: Extinction training and Extinction recall	Reinstatement
Struyf, Hermans, and Vervliet (2018)	Peak GS extinction: $n = 26$ Weak GS extinction: $n = 32$ CS extinction: $n = 26$	22.61(6.10)	Peak GS extinction: 22♀,4♂ Weak GS extinction: 25♀,7♂ CS extinction: 22♀,4♂	Facial stimuli	Electric shock	Peak GS and Weak GS groups: GS CS extinction group: CS	CSs, extinction GS, and novel GSs	CS GS	Yes	NA
Vervliet & Geens (2014)	Group Color: $n = 16$ Group Shape: $n = 15$	Group Color: 18.81 (0.91) Group Shape: 18.80(1.61)	Group Color: 10♀,6♂ Group Shape: 12♀,3♂	Colored geometric shapes	Electric shock	GSs	CSs	GS	Yes	NA
Vervliet et al. (2004)	ABA group: $n = 16$ AAB group: $n = 20$	Not provided	Not provided	Geometric shapes	Electric shock	ABA group: GSs AAB group: CSs	ABA group: CSs AAB group: GSs	CS GS	Yes	NA
Vervliet et al. (2005)	Generalization group: $n = 16$ Extinction group: $n = 16$	Not provided	Not provided	Geometric shapes	Electric shock	Generalization group: GSs Extinction group: CSs	CSs	CS GS	Yes	NA
Vervliet et al. (2010)	Group Color: $n = 16$ Group Shape: $n = 16$	Group Color: 19.06(1.34) Group Shape: 19.44(2.63)	Group Color: 13♀,3♂ Group Shape: 9♀,7♂	Geometric shapes with different colors	Electric shock	GSs	CSs	GS	Yes	NA
Waters et al. (2018)	Multiple stimuli extinction group: $n = 18$ CS extinction group: $n = 16$	23.5(7.7)	Multiple stimuli extinction group: 14♀,4♂ CS extinction group: 12♀,4♂	Images of dogs	Dog growling and scream	Multiple stimuli extinction group: CSs and GSs CS extinction group: CSs	CSs and novel GSs	CS MS	Yes	NA

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Table 1 (*continued*)

Study	Sample	Age (SD/range)	Sex	CS	US	Stimuli presented in extinction training	Stimuli presented in post-extinction test	Model (s)	Extinction training and post-extinction test assessed on the same day?	Manipulation between extinction training and post-extinction test
Waters et al. (2021)	Standard: n = 33 Multiple: n = 33 Extended: n = 33 Control: n = 33	Standard: 20.52(5.06) Multiple: 18.82(2.43) Extended: 21.00(5.27) Control: 19.88(4.05)	Standard: 23♀,10♂ Multiple: 23♀,10♂ Extended: 23♀,10♂ Control: 24♀,9♂	Images of dogs and plants	Dog growling and woman screaming	Standard: CSs Multiple: CSs & GSs Extended: CSs Other: Images unrelated to the CSs	CSs and novel GSs	CS MS	Yes	NA
Waters et al. (2023)	Standard: n = 32 Multiple: n = 32 Similar: n = 31 Different: n = 32	Standard: 21.57(5.17) Multiple: 22.66(6.41) Similar: 23.06(6.23) Different: 21.88(5.41)	Standard: 27♀, 5 ♂ Multiple: 27♀, 5 ♂ Similar: 26♀, 5 ♂ Different: 26♀, 6 ♂	Images of dogs	Dog growling and woman screaming	Standard: CS Multiple: CS & GS Similar: GS similar to CS & GS Different: GS dissimilar to CS & GSs	CSs and novel GSs	CS MS	Yes	NA
Wong and Lovibond (2020)	Experiment 1: ABA group: n = 50 AAA group: n = 50 Experiment 2: ABC group: n = 50 AAC group: n = 51	Experiment 1: 19.5(2.6) Experiment 2: 20.3(2.8)	Experiment 1: 74♀,26♂ Experiment 2: 74♀,27♂	Colored circles	Electric shock	ABA and ABC groups: GS AAA and AAC groups: CS	ABA and AAA groups: CS ABC and AAC groups: novel GS	CS GS	Yes	NA
Wong, Glück, Boschet, and Engelke (2020)	Linear: n = 20 Similarity: n = 34	Linear: 26.6(5.7) Similarity: 25.8(5.3)	Linear: 14♀,6♂ Similarity: 24♀,10♂	Geometric shapes	Electric shock	GS	CSs, extinction GS, and novel GSs	GS	Yes	NA
Wong et al. (2023)	Similarity group: n = 38 Linear group: n = 35	Similarity group: 24.58(3.97) Linear group: 23.14(3.80)	Similarity group: 29♀,9♂ Linear group: 27♀,8♂	Geometric shapes with different colors	Electric shock	GS	CSs, extinction GS, and novel GSs	GS	Yes	NA
Zbozinek and Craske (2018)	N = 125	21.95(3.51)	83♀,42♂	Colored geometric shapes and black-and-white drawings	Electric shock	Extinction CS+ group: CS Extinction Singular group: a single GS Extinction Variety group: 9 different GSs	CSs, extinction GS, and novel GSs	CS GS MS	Day 1: Acquisition and Extinction training Day 8: Extinction recall	Spontaneous recovery

Engelhard, 2018; Pittig, Wong, Glück, & Boschet, 2020). After response prevention extinction learning (i.e., when safety behaviors become unavailable during extinction training), participants still exhibited persistent generalized safety behaviors to the GSs in the post-extinction test.

2.2. Generalization of GS extinction learning

Most reviewed studies that employed the *generalization of GS extinction learning* model examined whether GS extinction learning generalizes to the CS+. In these studies, GSs that resemble the CSs (one threat-related GS and one safety-related GS) are typically presented during extinction training, followed by a post-extinction test in which the CSs are presented. These studies found persistent fear to the CS+ in the post-extinction test, i.e., limited *generalization of GS extinction learning* to the CS+, as indexed by stronger responding to the CS+ than to the CS- in the post-extinction test compared to a control condition that received CS extinction learning (Gerdes et al., 2020; Goldfarb et al., 2021; Vervliet et al., 2005; Zbozinek & Craske, 2018), or a recovery of fear to the CS+ (i.e., fear to the CS+ in the post-extinction test recovers to a similar level observed in fear acquisition; Vervliet, Kindt, Vansteenwegen, & Hermans, 2010; Vervliet & Geens, 2014; Wong & Lovibond, 2020).

Other studies examined the degree of GS extinction learning that generalizes to other novel GSs that resemble the CS+. Most of these studies found that GS extinction learning barely generalizes to other novel GSs, as reflected by stronger responding to a novel GS in post-extinction test compared to a control condition that received CS extinction learning (Wong & Lovibond, 2020; Zbozinek & Craske, 2018). So far, all studies above showed that GS extinction learning fails to prevent fear recovery to the CS+ or hardly generalizes to other novel GSs.

2.3. Generalization of multiple stimuli extinction learning

Waters et al. (2018, 2021, 2023) conducted a series of studies examining whether presenting multiple stimuli during extinction training enhances generalization of extinction learning. During extinction training, some participants received only the CSs (CS extinction group), CSs in addition to other GSs (Multiple stimuli extinction group), or only GSs perceptually similar (Similar GS extinction group) or different (Different GS extinction group) to the CSs. In a following post-extinction test, the CSs, a novel GS that was perceptually similar to the CS+, and another novel GS that was perceptually different to the CS+ were presented. In the post-extinction test, when compared to the CS extinction group, the Multiple stimuli extinction group showed stronger fear responses to the CSs but less fear responses to novel GSs that were perceptually similar to the CSs (Waters et al., 2018, 2021). In other words, when compared to standard CS extinction learning, including both the CSs and similar GSs during extinction training enhances generalized extinction learning to novel GSs, but not to the CSs. In addition, there was no evidence that the Similar GS extinction group (presenting only GSs similar to the CSs during extinction training) showed any differences in post-extinction test compared to the CS extinction group (Waters et al., 2023), preliminarily suggesting that only presenting GSs similar to the CS+ during extinction training poses similar *generalization of multiple stimuli extinction learning* than presenting both the CSs and GSs during extinction training. Therefore, these series of studies suggest that presenting both CSs and GSs during extinction training (Waters et al., 2018, 2021) or presenting GSs similar to the CS+ during extinction training (Waters et al., 2023) promote the *generalization of multiple stimuli extinction learning* to other novel GSs. Other neural imaging studies showed similar findings (Hagedorn et al., 2021, 2022). These studies presented both the CSs and similar GSs during extinction training in the multiple stimuli extinction condition while only presenting the CSs in the CS extinction condition. In a post-extinction test, the CSs and novel GSs were presented. The multiple stimuli extinction condition showed less activation of the “fear network”, including brain regions like the amygdala, insula, and dorsal anterior cingulate cortex, compared to the CS extinction condition. However, the skin conductance data was not consistent with the imaging results: while Hagedorn et al. (2021) found weaker skin conductance responses to the test stimuli in the multiple stimuli extinction condition compared to the CS extinction condition, no differences between conditions were observed in Hagedorn et al. (2022).

In contrast, Zbozinek and Craske (2018) included a group that received multiple GSs during extinction training. In a post-extinction test, this multiple GS extinction group showed more fear recovery to the CSs and stronger generalized fear to novel GSs when compared to a group that received standard CS extinction learning. On face value, although multiple stimuli extinction seemingly enhances the generalization of extinction learning (Hagedorn et al., 2021, 2022; Waters et al., 2018, 2021), all these findings included the CSs in addition to other GSs during extinction training. In contrast, there is limited evidence that only including multiple GSs during extinction training leads to great generalization of extinction learning (Waters et al., 2023; Zbozinek & Craske, 2018). Combined, these studies suggest that including multiple CSs and GSs during extinction training may play a major role in enhancing *generalization of multiple stimuli extinction learning*.

In sum, the different generalization of extinction learning models showed various degree of extinction generalization (see Table 2 for a summary). The literature shows that CS extinction learning effectively generalizes to other GSs in a post-extinction test, i.e., limited generalized fear to novel GSs after CS extinction learning. However, the strength of the *generalization of CS extinction learning* seemingly depends on the delay between extinction training and post-extinction test, and how different the novel GSs are from the CS+ presented in post-extinction test. In contrast, most studies observed weak *generalization of GS extinction learning*, i.e., strong fear recovery to the CS+ or substantial generalized fear to other novel GSs after GS extinction learning. While some studies (e.g., Hagedorn et al., 2021, 2022; Waters et al., 2018, 2021) showed that multiple stimuli extinction learning seemingly led to limited generalized fear in a post-extinction test, these studies included both the CSs and GSs in extinction training, while there was limited evidence that including only multiple GSs had similar effects (Waters et al., 2023; Zbozinek & Craske, 2018). Taken together, it seems that including the CS+ during extinction training plays a major role in enhancing generalization of extinction learning.

3. Factors modulating the strength of generalization of extinction learning

3.1. Clinical anxiety

3.1.1. Generalization of CS extinction learning

Klein et al. (2024) examined the effect of clinical anxiety on the generalization of CS extinction learning. Children and adolescents from 8 to 17 years old diagnosed with generalized anxiety disorders, social anxiety disorders, and/or specific phobias were recruited along with

Table 2
Summary of findings across generalization of extinction learning models. In the ‘Modulating Factors’ column, ↑ indicates factors enhancing generalization of extinction learning, ↓ indicates factors impairing generalization of extinction learning, and Ø indicates factors with limited evidence of effect. CS = *generalization of CS extinction learning*; GS = *generalization of GS extinction learning*; MS = *generalization of multiple stimuli extinction learning*.

Model	Strength of generalization	Key limitation(s)	Modulating factors
CS extinction	High	Difficult to reproduce the CS+ for treatment; generalization weakens over time	- Attention ↑ - Clinical anxiety ↓ - Memory reconsolidation Ø - Subclinical anxiety-related traits Ø
GS extinction	Low	Limited generalization	- Attention Ø - Expectancy violation ↑ - Subclinical anxiety-related traits Ø - Typicality ↑
Multiple stimuli extinction (including CS+ and GSs)	High	Difficult to reproduce the CS+ for treatment	- Expectancy violation Ø - Stress before *extinction training* ↑ - Stress before *extinction recall* ↓
Multiple stimuli extinction (including only GSs)	Low - moderate	Limited generalization	- Aerobic exercise ↑ - Memory reconsolidation Ø - Thought suppression ↓

age-matched healthy controls. Seven to ten days after CS extinction training, participants were presented with GS morphed between the CS+ and CS-. The clinical sample showed a wider fear generalization gradient compared to the healthy controls in threat appraisal ratings. Furthermore, the clinical sample showed stronger generalized responding in the late positive potential components to the GS most similar to the CS+, compared to the healthy controls. Enhanced late positive potential components have been previously used to indicate abnormal emotional processing in fear learning (e.g., Bacigalupo & Luck, 2018; Sperl, Wroblewski, Mueller, Straube, & Mueller, 2021; Stolz, Endres, & Mueller, 2019; Wiemer, Leimeister, & Pauli, 2021). Therefore, this pattern was interpreted as persistent generalized fear in the clinical sample. These patterns jointly suggest that clinical anxiety is associated with a weak *generalization of CS extinction learning*. To date, no studies have examined the effect of clinical anxiety on either the *generalization of GS extinction learning* or the *generalization of multiple stimuli extinction learning*.

3.2. Subclinical anxiety-related traits

3.2.1. Generalization of CS extinction learning

Klein et al. (2022) showed that healthy samples with severe generalized anxiety symptoms showed a broad fear generalization gradient to GSs morphed between the CSs after CS extinction learning (i.e., a weak *generalization of CS extinction learning*), as indexed by threat appraisal ratings.

Several studies examined the role of trait anxiety, a risk factor of clinical anxiety characterized by a strong likelihood to experience psychological arousal and distress across different situations (Watson & Clark, 1984), in *generalization of CS extinction learning*. Klein et al. (2020) found that trait anxiety was positively associated with stronger generalized safety behaviors to the most threat ambiguous GSs (i.e., GSs similar to both CS+ and CS-) after response prevention extinction learning to the CS+. In contrast, two studies (Endhoven et al., 2024; Klein et al., 2021) found no evidence of any trait anxiety effect on *generalization of CS extinction learning*. A similar construct, intolerance of uncertainty, characterized by an inability to tolerate negative responses evoked by a lack of information of the situation (Freeston, Rhéaume, Letarte, Dugas, & Ladouceur, 1994), was found to play no role in the *generalization of CS extinction learning* (Endhoven et al., 2024).

Behavioral inhibition, characterized by hypervigilant to threat and punishment (Carver, 2004), and social reticence, characterized by shy, and heightened avoidance to social interaction (Coplan, Rubin, Fox, Calkins, & Stewart, 1994), were found to have no effect on the generalization gradient along GSs morphed between the CSs after CS extinction learning (Michalska et al., 2019; Shechner et al., 2018). Harm avoidance, a risk factor characterized by an elevated level of threat anticipation and a great tendency to avoid potential threat (Cloninger, 1986), was found to associate with elevated distress ratings to the safety-related GS (the GS that resembles the safety-related CS-) after CS extinction learning (Gazendam et al., 2020).

3.2.2. Generalization of GS extinction learning

After GS extinction learning, trait anxiety and intolerance of uncertainty were found to associate with a broad generalization gradient of safety behaviors (Wong, Aslanidou, et al., 2023). These patterns seemingly align with the literature that anxiety-related psychopathology is linked to the excessive use of a “better safe than sorry” strategy (Van den Bergh, Brosschot, Critchley, Thayer, & Ottaviani, 2021) – the subclinical sample might have used excessive safety behaviors to the GSs to eliminate chances of threat occurrence. Gerdes et al. (2020) found that trait anxiety was associated with poor retention of safety learning, as indexed by an increase in threat expectancy ratings to the CS- in the post-extinction test. This pattern aligns with the literature that anxiety-related psychopathology is linked to impaired safety learning (see Duits et al., 2015; Kausche, Carsten, Sobania, & Riesel, 2024). In contrast, Wong and Lovibond (2020) found no evidence that trait anxiety impacts the degree of *generalization of GS extinction learning* to either the CS+ or a novel GS in the post-extinction test.

A deficit in attentional control, especially in the presence of a warning signal that predicts threat, is characterized by enhanced orientation towards the threat signal, even though this interferes with attention to other goal-related objects. This lack of attention control has been proposed to be a risk factor for the development of anxiety-related disorders and depression (Barry, Hermans, Lenaert, Debeer, & Griffith, 2013). There is mixed evidence regarding the effect of a deficit in attentional control in the *generalization of GS extinction learning*: while one study found that a deficit in attentional control was associated with impaired *generalization of GS extinction learning* to a novel GS in post-extinction test (Barry, Griffith, et al., 2016), another study found no evidence for this pattern (Barry et al., 2017).

In sum, while preliminary evidence suggests that subclinical generalized anxiety symptoms are associated with impaired *generalization of CS extinction learning*, there is limited to no evidence that other subclinical anxiety-related traits (e.g., trait anxiety, intolerance of uncertainty) have an effect on the different forms of generalization of extinction learning. The null findings in subclinical anxiety-related traits were perhaps not surprising given two reasons. First, the maladaptive effects of subclinical anxiety-related traits on extinction learning (and fear learning in general) are more likely to manifest under certain conditions, for instance, a condition with high threat ambiguity (Beckers, Krypotos, Boddez, Effting, & Kindt, 2013; Lissek, Pine, & Grillon, 2006; Morriss, Zuj, & Mertens, 2021). The reviewed studies might not have met these conditions thus masking the effects of subclinical anxiety-related traits on the generalization of extinction learning (see Morriss et al., 2021, for methods of creating layers of threat ambiguity). Second, another review highlighted the study of subclinical anxiety-related traits on fear learning is often exploratory (Wong, Aslanidou, et al., 2023), thus the sample size might not be well-powered to detect the effects of these traits on the generalization of extinction learning.

3.3. Cognitive factors

3.3.1. Attention

Attention plays a key role in associative learning by helping one to focus on relevant information while filtering out irrelevant details (Le Pelley, Mitchell, Beesley, George, & Wills, 2016; Mackintosh, 1975). Increased attention to the extinction stimulus may strengthen learning of the extinction stimulus – no US association, thus hypothetically enhancing its generalization. In addition, focusing one’s attention to the extinction stimulus arguably decreases the encoding of contextual information. This may decrease the context-dependency of the extinction memory, improving its retrieval and promoting generalization of extinction learning across different contexts.

3.3.1.1. Generalization of CS extinction learning.

Only one study examined the role of attention in the *generalization of CS extinction learning*. Klein et al. (2021) found that when participants were instructed to pay more attention to the CSs during extinction training, they exhibited less generalized fear to the GSs in a post-extinction test compared to participants in the control condition. However, this pattern was only observed in the startle eyeblink data but not in self-reported ratings.

3.3.1.2. Generalization of GS extinction learning.

Based on the notion that a GS evokes generalized fear due to its shared features with the CS+ (e.g., Blough, 1975; Rescorla, 1976), it is thought that if attention is directed to these shared features to the GS during extinction training (i.e., learning that the features that were previously associated with a threat now signal safety), extinction learning to the GS and its generalization would be enhanced. In contrast, if attention is directed to unique features of the GS during extinction training (i.e., features that had never been associated with a threat), *generalization of GS extinction learning* would be impaired. Barry et al. (2017) manipulated the focus of attention to different features of the GS during extinction training. In the Common group, participants' attention was directed to common features shared between the CS+ and the GS in extinction (i.e., threat-predicting features), whereas in the Unique group participants' attention was directed to features that were uniquely possessed by the GS (non-threat-predicting features). In the post-extinction test, a novel GS that shared some features with the CS+ and the extinction GS was presented. The Common group showed stronger *generalization of GS extinction learning* to a novel GS compared to the Unique group, as indexed by lower threat expectancy ratings to the novel GS in the post-extinction test. A similar study conducted by the same research group (Barry, Vervliet, & Hermans, 2016), however, found an opposite pattern: the Common group showed strong generalized fear to a novel GS in post-extinction test (i.e., a weak *generalization of GS extinction learning*) compared to the Unique group. The authors explained this unexpected pattern due to the Common group showing weak fear generalization from the CS+ to the extinction GS in the first place – thus participants might have perceived these common features as less aversive, leading to limited generalization of extinction learning.

3.3.2. *Typicality*

Typicality refers to how well an exemplar represents its category (Osherson, Smith, Wilkie, López, & Shafir, 1990). For instance, a cow is a highly typical mammal whereas a bat is an atypical mammal. Laboratory studies showed that training with typical CS+ exemplars led to greater generalized fear responses to novel GSs of the same category compared to training with atypical CS+ exemplars (Dunsmoor & Murphy, 2014; Wong & Beckers, 2021). This pattern, termed typicality asymmetry in generalization, is presumably due to training with highly typical CS+ exemplars promote the attribution of US onset to category membership, thus novel GSs of the same category evoke strong generalized fear. In contrast, training with atypical CS+ exemplars may have hindered the attribution of US onset to category membership, promoting instead the acquisition of individual exemplar – US associations. Therefore, fear generalization to novel exemplars is more limited. Following the principle of typicality asymmetry in fear generalization, the role of typicality was only examined in the *generalization of GS extinction learning model*.

3.3.2.1. Generalization of GS extinction learning. Following GS extinction learning, Scheveneels et al. (2017) instructed the typical group that the extinction stimulus was a typical exemplar of its category, while the atypical group was instructed that the extinction stimulus as an atypical exemplar of its category. Novel GSs were presented in the post-extinction test, and the typical group showed lower threat expectancy ratings to the threat-related GS (novel exemplars that belong to the same category of the CS+) compared to the atypical group. Thus, this provides preliminary evidence that presenting highly typical GS in extinction training promotes *generalization of GS extinction learning*.

3.3.3. *Expectancy violation*

Expectancy violation refers to a mismatch between an expected outcome and the actual outcome. Principles of error-correction models (e.g., Rescorla & Wagner, 1972) suggest that the larger expectancy violation is, the more learning takes place. Therefore, maximizing expectancy violation has been put forward as a major strategy to enhance extinction learning, and hence promotes generalization of extinction learning (Craske et al., 2014; Craske, Hermans, & Vervliet, 2018; Pittig et al., 2016). The role of expectancy violation was examined in *generalization of GS extinction learning* and *generalization of multiple stimuli extinction learning*.

3.3.3.1. Generalization of GS extinction learning. A GS typically evoke less conditioned fear compared to the CS+ due to generalization decrement (Mackintosh, 1974). Therefore, extinction learning to a GS typically yields less expectancy violation compared to CS extinction learning, resulting in limited extinction learning and its generalization. Struyf et al. (2018) examined whether employing a GS that evokes stronger conditioned fear than the CS+ during extinction training would enhance *generalization of GS extinction learning*. Their study used a stimulus dimension of facial stimuli with increasingly fearful expression. The stimulus with the least fearful expression served as a CS- whereas the stimulus in the middle of the stimulus dimension (i.e., moderately fearful expression) served as the CS+. During extinction training, one group received non-reinforced CS+ trials (CS extinction group), one group received a GS intermediate of the CS+ and the CS- along the dimension (i.e., a weak fearful expression; weak GS extinction group), whereas one group received a GS with the most intense fearful expression (peak GS extinction group). During extinction training, both the CS+ extinction group and peak extinction group showed similarly high levels of threat expectancies to the extinction stimulus, suggesting that the peak GS+ evoked similar levels of fear as the CS+ (i.e., no generalization decrement for the peak GS). In a following post-extinction test, all stimuli along the stimulus dimension were presented. Both the peak GS extinction group and the CS+ extinction group showed flatter generalization gradients compared to the weak GS extinction group. Of note, the peak GS extinction group showed less fear to the peak GS during post-extinction test compared to the CS+ extinction group. Combined, this finding suggests that using a peak GS that evokes strong expectancy violation during extinction training promotes *generalization of GS extinction learning*.

Two additional studies have also supported the idea that presenting a GS that elicits strong expectancy violation enhances the *generalization of GS extinction learning* (Wong et al., 2020; Wong, Lee, Engelke, & Pittig, 2023). In these two studies, a continuous stimulus dimension was used (e.g., a green-blue continuous dimension). Stimulus on one extreme end (e.g., a green stimulus) served as the CS- whereas the stimulus intermediate of the stimulus dimension (e.g., an aqua stimulus) served as the CS+. In a following generalization test, all stimuli along the stimulus dimension were presented. Distinct generalization gradients were observed, due to participants using different rules to guide their generalization of fear. Participants who responded on a similarity rule (e.g., the more aqua color a stimulus is, the more likely it signals a US) showed a bell-shaped gradient with responding peaked at the CS+ that gradually decreases to stimuli towards the two extreme ends of the stimulus dimension (lowest responding to the bluest and greenest stimuli). In contrast, participants who responded on a linear rule (e.g., the bluer the stimulus is, the more likely it signals a US) showed a linear increase in responding across the stimulus dimension, with responding peaked at the bluest stimulus. Therefore, one can expect that presenting the bluest stimulus in extinction evokes limited expectancy violation for the similarity rule group whereas it evokes strong expectancy violation to the linear rule group. Consistent with this expectation, presenting the bluest GS in extinction training resulted in the linear rule group showing less generalized fear and safety behaviors across all GSs compared to the similarity rule group. That is, the linear rule group showed greater *generalization of GS extinction learning* compared to the similarity rule group. These two studies put forward the notion that generalization rules can be seen as threat beliefs, and these threat beliefs determine how fear generalizes. Importantly, these findings suggest that certain GSs evoke strong or limited expectancy violation, depending on one's threat beliefs. Therefore, identifying different threat beliefs and select GSs that maximize expectancy violation help promote *generalization of GS extinction learning*.

3.3.3.2. Generalization of multiple stimuli extinction learning. Traditionally, exposure-based treatments utilize exposure hierarchies, where feared stimuli or situations are systematically selected and presented in a gradually increasing order of fear intensity (Foa & Kozak, 1986). This contradicts with a more recent notion that maximizing expectancy violation enhances extinction learning (Craske et al., 2014), as limited expectancy violation would be evoked if the extinction learning follows a hierarchical fashion. Instead, randomizing the exposure order of the hierarchy is thought to evoke stronger expectancy violation compared to the traditional progressive fashion (Craske et al., 2014; Knowles & Olatunji, 2019). Following this idea, Scheveneels et al. (2019) presented the CSs and GSs morphed between the CSs during extinction learning. The hierarchical exposure group received the stimuli in an increasing order of fear intensity, that is, the CS- was always presented first, followed by a morphed GS that was most similar to the CS-, all the way up to the CS+. The random exposure group received the same set of stimuli in a randomized order. In a post-extinction test, the CSs and a novel GS were presented. As expected, expectancy violation was higher in the random exposure group compared to the hierarchical exposure group throughout the extinction training phase, as indexed by higher threat expectancy ratings across all extinction trials for the former compared to the latter. However, there was no evidence for any group differences in fear responding to the stimuli in the post-extinction test, suggesting no evidence that random exposure is more effective in enhancing generalization of extinction learning than the traditional hierarchical exposure.

3.3.4. Thought suppression

One cognitive-related strategy to enhance extinction learning (and its generalization) is thought suppression. Suppressing one's thought about the extinction stimulus during extinction training is hypothesized to downregulate hippocampal activity (Anderson & Hanslmayr, 2014; Bjork, Bjork, & Anderson, 1998), which is responsible for integrating contextual information (Maren, Phan, & Liberzon, 2013). Thus, this is thought to decrease the dependency on contextual information, strengthening the retrieval of the extinction memory (and its generalization). There is one study to date (Hennings et al., 2021) that examined the role of thought suppression in the *generalization of multiple stimuli extinction learning.*

3.3.4.1. Generalization of multiple stimuli extinction learning. Hennings et al. (2021) used a categorical conditioning protocol in which every stimulus was only presented once. CS+ exemplars from two categories (animal and tool) that signaled a US whereas CS- exemplars from one category (food) that signaled the absence of a US. During extinction training, multiple GS exemplars from the three CS categories were presented. Participants were asked to suppress the mental images for one CS+ category (e.g., animal) but not the other (e.g., tool). Twenty-four hours later, novel GS exemplars from the three categories were presented in a renewal test. GS exemplars from the two CS+ categories evoked higher threat expectancies to the GS exemplars from the CS- category, reflecting renewal of fear generalization. In contrast to the authors' expectation, GS exemplars from the suppressed CS+ category (e.g., novel animals) evoked higher threat expectancies than the GS exemplars from the non-suppressed CS+ category (e.g., novel tools). The authors interpreted this unexpected pattern as thought suppression acting as a conditioned inhibitor; participants attributed US absence to thought suppression, thus preventing extinction learning to these GSs (protection from extinction; Lovibond, Davis, & O'Flaherty, 2000; Rescorla, 2003).

In sum, the role of cognitive factors in the generalization of extinction learning were examined in various generalization of extinction learning models. Preliminary evidence suggests that directing attention to the extinction stimulus and its shared perceptual features with the CS+, maximizing expectancy violation during extinction training, and presenting highly typical extinction stimuli each enhance the generalization of extinction learning. In contrast, preliminary evidence suggests that thought suppression impairs this process.

3.4. Neuro- and biobehavioral factors

3.4.1. Memory reconsolidation

Memory reconsolidation refers to a process when a memory is reactivated and temporarily becomes vulnerable to modification or disruption; protein synthesis is required to restabilize this memory back into long-term memory (McKenzie & Eichenbaum, 2011; Riccio, Millin, & Bogart, 2006). Interfering the reconsolidation process of a memory via a pharmacological approach (e.g., Nader, Schafe, & Le Doux, 2000) or a behavioral approach (e.g., Monfils, Cowansage, Klann, & LeDoux, 2009) blocks memory stabilization or incorporates new information to the memory. In cases of interfering the reconsolidation process of fear memories, both approaches are believed to lead to a permanent loss of the fear memory. The role of disrupting the process of memory reconsolidation was examined in *generalization of CS extinction learning* and *generalization of multiple stimuli extinction learning.*

3.4.1.1. Generalization of CS extinction learning. Soeter and Kindt (2012) examined whether disrupting memory reconsolidation combined with CS extinction learning would decrease generalized fear to novel GSs. During fear acquisition, participants learnt that two different CS+ (spider and gun) signaled shock whereas one CS- (mug) signaled the absence of shock. Twenty-four hours after fear acquisition, propranolol HCI, a β-adrenergic receptor antagonist that inhibits protein synthesis, was administered either before or after a non-reinforced CS+ reminder (spider), which destabilized the reconsolidation of this specific CS+ memory. Another twenty-four hours later, extinction learning to all the CSs took place, immediately followed by reinstatement manipulation. In a following post-extinction test, GSs categorically and semantically related to the CSs were presented. Participants showed weaker startle eyeblink responses to GSs related to the reactivated CS+ (spider) compared to the GSs related to the non-reactivated CS+ (gun); however, this pattern was not observed in skin conductance and threat expectancy ratings. This study provides some evidence that disrupting the reconsolidation process of the CS+ memory combined with CS extinction learning enhances *generalization of CS extinction learning.* More recently, using a behavioral approach, Meir Drexler, Merz, Lissek, Tegenthoff, & Wolf (2019) used a weakened US to reactivate the fear memory followed by CS extinction training during the reconsolidation window. However, generalized fear responses persisted to perceptually similar GSs in a post-extinction test.

3.4.1.2. Generalization of multiple stimuli extinction learning. Kroes et al. (2017) used a 3-day category conditioning procedure in which each CS was only presented once. On the first day, the CS+ category (e.g., bird) signaled US onset whereas the CS- category (e.g., fish) signaled the absence of US onset. On the second day, one group received a novel GS+ exemplar (a novel GS that belonged to the CS+ category) to activate the fear memory, whereas a control group received no such reminder. Immediately after, extinction training took place with multiple novel GS exemplars from the CS categories presented. On the third day, a reinstatement test was conducted with novel GS exemplars from the CS categories presented. Both groups showed comparable differential skin conductance responses to the GSs, suggesting no evidence that interfering fear memory reconsolidation enhances *generalization of multiple stimuli extinction learning.*

3.4.2. Stress

It has been proposed that the timing of stress administration has different impacts on extinction learning and retrieval of extinction memory (Meir Drexler, Merz, Jentsch, & Wolf, 2019. Stress induction before extinction training is thought to strengthen the consolidation of extinction memory and decreases its context dependency (e.g., Meir Drexler, Hamacher-Dang, & Wolf, 2017; Meir Drexler, Merz, & Wolf, 2018). The role of stress in the generalization of extinction learning has been examined in *generalization of multiple stimuli extinction learning.*

3.4.2.1. Generalization of multiple stimuli extinction learning. Hagedorn et al. (2022) found that stress administration before extinction training abolished the differential activation of the dorsal anterior cingulate cortex in the multiple stimuli extinction condition but not in the CS extinction condition, i.e., stress administration before multiple stimuli extinction learning decreases the activation of one region of the "fear network". In contrast, stress administration before extinction recall has been found to disrupt the retrieval of extinction memory (Kinner, Merz, Lissek, & Wolf, 2016; Raio, Brignoni-Perez, Goldman, & Phelps, 2014). Consistent with the literature, Hagedorn et al. (2021) found that stress induction before extinction recall led to an increase in amygdala and insula activation, and an increase in skin conductance responses in the multiple stimuli extinction condition. In sum, the different effects of stress on extinction learning and extinction recall observed in standard CS extinction learning seem to extend to multiple stimuli extinction learning, i.e., stress enhances *generalization of multiple stimuli extinction learning* when administered before extinction training, while it impairs *generalization of multiple stimuli extinction learning* when administered before extinction recall.

3.4.3. Aerobic exercise

Recent evidence has suggested that aerobic exercise administered before or after extinction training improves the consolidation of the extinction memory, thus reducing return of fear (see Roquet & Monfils, 2018). The role of aerobic exercise in the generalization of extinction learning has been investigated in *generalization of multiple stimuli extinction learning.*

3.4.3.1. Generalization of multiple stimuli extinction learning. Crombie et al. (2023) examined whether aerobic exercise improves the consolidation of GS extinction memory and its generalization. Participants first acquired differential fear responses to CS exemplars from two categories, animals and tools. On a second day, multiple novel GS exemplars from the two CS categories were presented during extinction training. After extinction learning to multiple GS exemplars, the exercise group engaged in moderate intensity exercise whereas the control group engaged in light intensity exercise. On a third day, the CSs of acquisition, the extinction GSs, and novel GSs were presented to both groups. The exercise group showed less threat expectancy across all test stimuli compared to the control group, suggesting that a moderate intensity of exercise enhances *generalization of multiple stimuli extinction learning.* However, given that responding to all test stimuli (the CSs, the extinction GSs, and the novel GSs) were collapsed together, it remains unclear whether aerobic exercise specifically reduces fear recovery to the extinction GSs, reduces fear recovery to the CSs, decreases generalized fear to novel GSs, or a combination of these patterns.

In sum, inducing stress before extinction training and carrying out aerobic exercise after extinction training seem to be promising for enhancing the generalization of extinction learning. In contrast, it remains unclear whether memory reconsolidation has any robust effect on the generalization of extinction learning. Given the mixed findings of interfering the memory reconsolidation of fear memories (e.g., Chalkia et al., 2020; Chalkia, Van Oudenhove, & Beckers, 2020; Kindt & Soeter, 2013; Kredlow, Orr, & Otto, 2018), further investigation is needed to determine the role of fear memory reconsolidation in the generalization of extinction learning.

4. Mechanisms of the generalization of extinction learning

The general finding that including the CS+ during extinction training enhances generalization of extinction learning is generally in line with the elemental accounts. These accounts suggest that each stimulus consists numerous hypothetical elements (Blough, 1975; Mclaren & Mackintosh, 2002). The more two stimuli perceptually resemble each other, the more elements they share. Thus, including the CS+ in extinction training allows all the elements that previously gained excitatory strength to now acquire inhibitory strength. As a results, when novel GSs are encountered during post-extinction test, any shared elements with the CS+ already have inhibitory strength, leading to limited or no generalized fear. In contrast, while presenting a GS or multiple GSs during extinction training allows the elements they share with the CS+ to gain inhibitory strength, the elements not shared between the CS+ and extinction GSs remained their excitatory strength. Therefore, test stimuli with these elements can still evoke fear, limiting the generalization of extinction learning.

Fear also generalizes to novel stimuli that are perceptually different but conceptually related (e.g., Dunsmoor et al., 2012; Dymond et al., 2011). Indeed, fear generalization has been suggested to be similar to inductive reasoning, as both processes involve inferring the properties of novel objects based on the known properties of a target object (Dymond et al., 2015). Recent evidence provides some empirical support for this notion as factors that increase the strength of inductive reasoning also increase the breadth of fear generalization (e.g., Dunsmoor & Murphy, 2014; Fan et al., 2022; Wong & Beckers, 2021). For instance, properties of highly typical premises that are good representators for their category, lead to stronger inference that a novel premise also possesses the same properties in the inductive reasoning literature (Osherson et al., 1990). Likewise, training with highly typical CS+ exemplars in a fear conditioning framework led to stronger fear generalization to novel GS exemplars of the same category compared to training with atypical exemplars (Dunsmoor & Murphy, 2014; Wong & Beckers, 2021). Following this logic, these factors may also affect generalization of extinction learning in a similar fashion. Preliminary evidence suggests that presenting highly typical GSs in extinction promotes generalization of extinction learning (Scheveneels et al., 2017). However, although presenting multiple numbers of premises have been found to promote induction (e.g., learning that cows, bears, and horses have a specific property promotes the inference that all mammals share this specific property; Heit, 2000; Osherson et al., 1990), presenting multiple GSs during extinction training does not seem to promote generalization of extinction leaning (e.g., Waters et al., 2023; Zbozinek & Craske, 2018), unless the CSs were included along with the GSs during extinction training (Hagedorn et al., 2021, 2022; Waters et al., 2018, 2021). Future studies are required to bridge the inductive reasoning literature with generalization of extinction learning.

The elemental account and inductive reasoning account seem to overlap in their explanations of the generalization of extinction learning. For instance, the inductive reasoning account can account for perceptual generalization based on the induction that when a novel stimulus shares more perceptual features with the target premise, the more likely they share similar properties. Likewise, the elemental account can also explain conceptual generalization of extinction learning, as exemplars in the same category tend to share similar perceptual features (e.g., most mammals have fur or hair). Future studies can explore how these two accounts may jointly predict the degree of the generalization of extinction learning.

5. A pathway for the return of fear?

Although enhancing the *generalization of CS extinction learning* has been proposed as a strategy to improve the effectiveness of exposure-based treatments (e.g., Pittig et al., 2016), extinction learning targeting the CS+ may not fully represent the dynamics of exposure-based treatments in real-life scenarios. As noted previously, the exact stimulus of fear acquisition (the CS+) is unlikely to be replicated for exposure sessions. Instead, exposure-based treatments typically use stimuli resembling the stimulus of fear acquisition, akin to extinction learning with GS(s). This review shows that extinction learning with GS(s) is generally successful per se, as evidenced by limited fear responses to the extinction stimuli at the end of extinction trials. This parallels the reduction of fear towards the exposure stimuli at the end of an exposure session. However, the generalization of extinction learning from GS(s) to novel test stimuli is limited, resulting in substantial generalized fear. This limited generalization of extinction learning to GS(s) can be seen as the return of fear in real-life situations. When clients encounter novel stimuli (new GSs) resembling the original fear-evoking stimulus (CS+) after treatment, fear returns due to ineffective generalization of GS extinction learning (see Wong & Lovibond, 2020).

6. Clinical implications and future directions

This review shows that the generalization of extinction learning is most robust when the original stimulus of fear acquisition (CS+) is included during extinction training, a finding that poses challenges for clinical translation given the impracticality of reproducing the exact fear-evoking stimulus in treatment. However, emerging preliminary evidence suggests that generalization of extinction learning can be enhanced even when only GSs are presented during extinction training, bridging this translational gap. First, the selected GSs presented during extinction training pertain to the strength of the generalization of extinction learning. For instance, GSs that evoke strong expectancy violation enhances extinction learning and its generalization to other novel stimuli, as supported by laboratory findings (Struyf et al., 2018; Wong et al., 2020; Wong, Lee, Engelke, & Pittig, 2023). Parallel clinical studies also indicate that exposure treatments designed to maximize expectancy violation are associated with better treatment outcomes (Baker et al., 2010; Deacon et al., 2013; Kircanski et al., 2012). Second, flanker strategies can be used to enhance the generalization of GS-only extinction learning. For instance, lab findings showed that aerobic exercise before or after extinction training with GSs strengthens its generalization (Crombie et al., 2023), while clinical evidence also suggests that aerobic exercise improves treatment effectiveness (Merom et al., 2008; Powers et al., 2015). Future research should explore whether other promising lab-supported strategies, such as using highly typical GSs or inducing stress before extinction training, can similarly enhance treatment outcome in which the CS+ is usually unavailable. There are also other lab-supported strategies that improves extinction retention after CS extinction learning but have yet been tested in generalization of extinction learning. For example, inducing positive affect before extinction learning (Zbozinek, Holmes, & Craske, 2015) or pairing the extinction stimulus with a novel outcome (Dunsmoor, Campese, Ceceli, LeDoux, & Phelps, 2015). Future studies should explore whether these strategies can be applied to enhance the generalization of extinction learning.

While I have argued that ineffective generalization of extinction learning may also explain the return of fear in real-life scenarios, future studies are needed to further test this notion. One way to examine this is by including the extinction stimulus as a control stimulus in the post-extinction test. An increase in fear towards this stimulus would merely indicate fear recovery. If the fear response to another novel GS (while controlling for generalized fear to it) in post-extinction test is greater than the fear recovery to the extinction stimulus, this would more clearly reflect ineffective generalization of extinction learning beyond mere fear recovery.

Future research should also aim to establish a consensus on the delay between extinction training and the post-extinction test. This review highlights that most studies conducted the post-extinction test immediately after extinction training, while only a few delayed this assessment. Testing extinction retention after a delay is arguably more ecologically valid, as it allows time for the extinction memory to reconsolidate (Quirk & Mueller, 2008). During the retention test, researchers can evaluate whether the extinction memory can be retrieved and to what extent it inhibits generalized fear to novel GSs.

Although this review argues that GS extinction learning more accurately reflects real-life exposure-based treatments, it does not diminish the importance of CS extinction learning models. Over the past decades, the CS extinction learning models have significantly advanced our understanding of the theoretical background and mechanism underlying extinction learning (e.g., Bouton, 1993, 2004). Continued research on CS extinction learning is still crucial to advancing our knowledge of GS extinction learning and the return of fear.

7. Conclusion

In summary, this review provides a novel synthesis of findings from the three forms of generalization of extinction learning, including *generalization of CS extinction learning*, *generalization of GS extinction learning*, and *generalization of multiple stimuli extinction learning*. It is clear that CS extinction learning generalizes strongly to other novel GSs, i.e., limited to no generalized fear to novel GSs after extinction learning to the stimulus of fear acquisition. However, this *generalization of CS extinction learning* seems weak when the extinction training phase and post-extinction test are separated for at least 24 h, presumably due to the failure to retrieve the extinction memory via spontaneous recovery.

While both *generalization of GS extinction learning* and *generalization of multiple stimuli extinction learning* models arguably more closely reflect exposure-based treatments, the reviewed findings showed very limited generalization of extinction learning in these models, unless the CSs were also presented during extinction training. Based on these findings, this review proposes that ineffective generalization of extinction learning to GS(s) may be an alternative path for the return of fear. Despite the underwhelming results in the generalization of GS(s) extinction learning, there are some promising strategies to enhance the generalization of extinction learning, such as aerobic exercise after extinction training, or presenting GSs that maximize expectancy violation during extinction training. Additional strategies that may enhance the generalization of extinction learning should be addressed in future research.

Authors' declaration

I wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

I confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed.

I confirm that I have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing I confirm that I have followed the regulations of my institution concerning intellectual property.

I further confirm that any aspect of the work covered in this manuscript that has involved either experimental animals or human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

I understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. I confirm that I have provided a current, correct email address which is accessible by the Corresponding Author and which has been configured to accept email from h.k.wong@essb.eur.nl

Declaration of competing interest

There are no competing interests to declare.

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Appendix A. Supplementary data

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Data availability

No data was used for the research described in the article.

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