# Stress-induced reliance on habitual behavior is moderated by cortisol reactivity

Smeets, T.; Van Ruitenbeek, P.; Hartogsveld, B.; Quaedflieg, Conny W.E.M.

*Published in:*
Brain and Cognition

*DOI:*
10.1016/j.bandc.2018.05.005

*Publication date:*
2019

*Document Version*
Publisher's PDF, also known as Version of record

Brain and Cognition 133 (2019) 60–71

Contents lists available at ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

# Stress-induced reliance on habitual behavior is moderated by cortisol reactivity

T. Smeets*, P. van Ruitenbeek, B. Hartogsveld, Conny W.E.M. Quaedflieg

*Department of Clinical Psychological Science, Faculty of Psychology and Neuroscience, Maastricht University, The Netherlands*

ARTICLE INFO

*Keywords:*
Stress
Cortisol
Habits
Instrumental learning

ABSTRACT

Instrumental learning, i.e., learning that specific behaviors lead to desired outcomes, occurs through goal-directed and habit memory systems. Exposure to acute stress has been shown to result in less goal-directed control, thus rendering behavior more habitual. The aim of the current studies was to replicate and extend findings on stress-induced prompting of habitual responding and specifically focused on the role of stress-induced cortisol reactivity. Study 1 used an established outcome devaluation paradigm to assess goal-directed and habitual control. Study 2 utilized a modified version of this paradigm that was intended to establish stronger habitual responding through more extensive reward training and applying a relevant behavioral devaluation procedure (i.e., eating to satiety). Both studies failed to replicate that stress overall, i.e., independent of cortisol reactivity, shifted behavior from goal-directed to habitual control. However, both studies found that relative to stress-exposed cortisol non-responders and no-stress controls, participants displaying stress-induced cortisol reactivity displayed prominent habitual responding. These findings highlight the importance of stress-induced cortisol reactivity in facilitating habits.

## 1. Introduction

Stress is omnipresent in our modern society. We all experience it for various reasons (e.g., near-impossible deadlines, daily hassles), and most of us think of stress as an unpleasant fact of everyday life. Exposure to stressful events activates the autonomic nervous system (ANS) and the hypothalamus-pituitaryadrenal (HPA) axis, causing the release of catecholamines (e.g., adrenalin and noradrenalin) and glucocorticoids (cortisol in humans and monkeys; corticosterone in many other species) by the adrenal cortex into the bloodstream (Ulrich-Lai & Herman, 2009). The stress-induced increase in activity of the ANS and HPA stress systems leads to physiological and cognitive-behavioral alterations that served an adaptive purpose (i.e., to increase chances of survival; de Kloet, Joels, & Holsboer, 2005; McEwen, 1998, 2008). For example, acute stress responses via their joint actions on brain structures central to memory (e.g., the basolateral amygdala; see de Quervain, Schwabe, & Roozendaal, 2017; Roozendaal & McGaugh, 2011) endorse the formation of lasting memories by enhancing memory consolidation (e.g., Smeets, Otgaar, Candel, & Wolf, 2008) whilst concurrently impairing memory retrieval processes (e.g., see Shields, Sazma, McCullough, & Yonelinas, 2017; Wolf, 2009, 2017, for comprehensive reviews). Moreover, stress affects instrumental learning by promoting the favorable use of rather rigid and undemanding habits over flexible yet cognitively demanding goal-directed behavior (Schwabe & Wolf, 2009, 2010; for review see Schwabe & Wolf, 2013; Schwabe, Wolf, & Oitzl, 2010; Wirz, Bogdanova, & Schwabe, 2018).

Learning that specific behaviors lead to specific desired outcomes, so-called instrumental learning, is thought to be under the control of a goal-directed and a habit system (O'Doherty, Cockburn, & Pauli, 2017; Wood & Rünger, 2016). An outcome devaluation paradigm is generally used to determine whether behavior is controlled by the goal-directed or the habit system. Here, an outcome is devalued and subsequent responding to that outcome is observed. If responding to the devalued outcome is reduced, behavior is interpreted as being goal-directed. Alternatively, if continued responding to a devalued outcome is observed, then behavior is said to be controlled by the (stimulus-response governed) habit system. The modulation of goal-directed and habitual control by exposure to acute stress was first observed in humans in a seminal study by Schwabe and Wolf (2009). Using a selective outcome devaluation paradigm originally developed by Valentin, Dickinson, and O'Doherty (2007), the authors found that participants exposed to acute stress before instrumental learning were insensitive to outcome devaluation, and consequently responded more habitual than non-stressed controls. In a follow-up study, Schwabe and Wolf (2010) demonstrated

* Corresponding author at: Department of Clinical Psychological Science, Faculty of Psychology and Neuroscience, Maastricht University, P.O. Box 616, 6200 MD Maastricht, The Netherlands.
*E-mail address:* tom.smeets@maastrichtuniversity.nl (T. Smeets).

https://doi.org/10.1016/j.bandc.2018.05.005
Received 10 February 2018; Received in revised form 14 May 2018; Accepted 14 May 2018
Available online 25 May 2018

that stress influences the expression of habitual behavior, with stress after instrumental learning and outcome devaluation leading to more habitual responding. Since then, several studies have shown that acute stress shifts behavior from goal-directed to habitual responding (for review see Schwabe & Wolf, 2013; Wirz et al., 2018).

The finding that stress prompts the use of habits has been reported not only in studies using Valentin et al.'s (2007) instrumental learning paradigm, but also in studies that used probabilistic classification learning tasks (e.g., Schwabe & Wolf, 2012; Schwabe, Tegenthoff, Höffken, & Wolf, 2013) or sequential decision making tasks measuring model-based versus model-free learning (indicative of goal-directed vs. habitual learning, respectively; Otto, Raio, Chiang, Phelps, & Daw, 2013; Radenbach et al., 2015). However, in those latter sequential decision making studies the effect of stress on habitual responding was restricted to participants with low working memory (Otto et al., 2013) or when acute stress was combined with chronic stress effects (Radenbach et al., 2015). Furthermore, using a widely-used outcome devaluation paradigm that assesses the relative balance between goal-directed and habitual responding following instructed devaluation in a slips-of-action test (de Wit, Niry, Wariyar, Aitken, & Dickinson, 2007), Fournier, d'Arripe-Longueville, and Radel (2017) found no effect of stress applied prior to instrumental learning on the fostering of habits. Thus, it seems that the finding of acute stress encouraging the use of habits has not been unequivocal, and that this may have to do with differences in how goal-directed and habitual behavior is operationalized. Interestingly, several studies reported significant correlations between stress-induced cortisol increases and the shift from goal-directed to habitual responding (Otto et al., 2013; Radenbach et al., 2015; Schwabe & Wolf, 2010; Schwabe, Höffken, Tegenthoff, & Wolf, 2011; Vogel et al., 2017; for an exception see Schwabe & Wolf, 2012). This demonstrates the importance of cortisol as a potential mechanism underlying the stress-induced shift towards habits.

With this in mind, the aim of the current studies was to replicate and extend findings on stress-induced shifting to habitual responding by specifically focusing on stress-induced cortisol reactivity (i.e., differences between cortisol responders and non-responders). Study 1 used an established outcome devaluation paradigm to dissociate goal-directed from habitual action (de Wit et al., 2007; see also Fournier et al., 2017), while in Study 2 we modified this paradigm to establish stronger habitual responding. Study 2's modified instrumental learning paradigm included more extended instrumental learning and rewarding participants for learning the correct associations, and applied a relevant behavioral devaluation (i.e., eating to satiety) instead of an instructed (cognitive) devaluation (see also de Houwer et al., in press). We expected that acute stress would lead to a stronger expression of habitual responding compared to a non-stressed control group, and that this effect would be more pronounced in stressed participants displaying high cortisol responses (Study 1 and Study 2) and when more ideal conditions are created to induce a shift from goal-directed to habitual responding by using the modified instrumental learning paradigm (Study 2).

## 2. Study 1

### 2.1. Study 1 Method

#### 2.1.1. Participants

Seventy-two healthy undergraduates (20 men; 52 women) with a mean age of 21.5 years (*range* = 18–28; *SD* = 2.31) and a normal Body Mass Index (BMI in kg/m$^2$; *range* = 18.1–27.6; *Mean* = 22.27; *SD* = 2.39) enrolled in Study 1. Participants were randomly allocated to a stress or no-stress control group. Groups did not differ in age ($t_{70}$ = 1.44, $p$ = .15), BMI ($t_{70}$ = 0.77, $p$ = .44] or distribution of men and women ($\chi^2_{(1,N=72)}$ = 2.49, $p$ = .11]. Participants were recruited via advertisements that requested volunteers for a study examining cognition in response to physical and mental challenges. Eligibility was assessed using a semi-structured interview, with cardiovascular diseases, severe physical illnesses (e.g., fibromyalgia), hypertension, endocrine disorders, current or lifetime psychopathology, substance abuse, heavy smoking (> 10 cigarettes/day) or being on any kind of medication known to affect the HPA-axis serving as exclusion criteria. Test protocols were approved by the standing ethics committee of the Faculty of Psychology and Neuroscience, Maastricht University, and complied with the declaration of Helsinki (v. 2013). All participants provided informed consent and received a small financial reward or partial course credit in return for their participation.

#### 2.1.2. Stress vs. no-stress control procedure

The stress group was exposed to the Maastricht Acute Stress Test (MAST; Smeets et al., 2012, see also Quaedflieg, Meyer, van Ruitenbeek, & Smeets, 2017; Shilton, Laycock, & Crewther, 2017), an effective acute stressor that combines psychological and physical components. The MAST commences with a 5-minute instruction phase, followed by a 10-minute acute stress phase that involves repeatedly inserting the non-dominant hand in ice-cold water (4 °C), alternated with a challenging mental arithmetic task entailing the counting backwards in steps of 17 starting at 2043 as fast and accurate as possible. To induce social evaluative threat, participants were videotaped during the MAST and negative feedback was provided on their performance.

The control group completed a validated no-stress control condition that was equal in length and involved similar operations as the MAST, but without the stress-eliciting components. Here, participants immersed their non-dominant hand in lukewarm water (35 °C) and performed a simple counting test without being videotaped or receiving negative feedback (see Smeets et al., 2012, Exp. 3).

#### 2.1.3. Neuroendocrine stress responses

As an index of neuroendocrine reactivity, salivary cortisol was sampled via synthetic Salivette (Sarstedt®, Etten-Leur, the Netherlands) devices immediately before (i.e., $t_{baseline}$) and 1, 20, and 35 min after end of the stress/control procedure (i.e., $t_{+01}$, $t_{+20}$, $t_{+35}$). Samples were stored at −20 °C immediately on collection. Cortisol levels were determined by a commercially available chemiluminescence immunoassay (IBL Intl, Hamburg, Germany), with mean intra- and inter-assay coefficients of variation < 8%.

#### 2.1.4. Instrumental learning task

Participants engaged in an instrumental learning task (de Wit et al., 2007) that was presented to them as a game in which they were required to earn as many points as possible to earn certain food rewards.

In the first, *instrumental learning* stage, participants had to learn by trial-and-error 6 different Stimulus-Response-Outcome (SRO) associations. On each trial, a picture of a closed box was shown with a stimulus (e.g., an orange) depicted on it, and participants were instructed to give an instrumental response by pressing with their dominant hand either the left or the right response key. If they pressed the correct key, the box opened and an outcome stimulus was shown inside the box (e.g., an apple) and points were earned (ranging from 5 to 1 depending on the speed with which they responded). If they pressed the incorrect key, the box opened but remained empty and no points were earned. All SRO combinations had a 100% contingency rate, meaning that each stimulus could serve as a perfect cue for the related response-outcome contingency. The instrumental learning phase is self-paced and comprised 12 blocks of 12 trials such that each SRO combination was presented twice per block in a random order (144 trials in total). After each block, participants were provided with feedback by showing their block score and cumulative total score thus far. SRO instrumental learning performance was determined by calculating the correct response rate for each block. To familiarize themselves with the task, participants received a 12-trial demo training with stimuli and outcomes that were unrelated to those used in the actual task.

The second stage of the instrumental learning task consists of a *slips-of-action task* to measure the relative balance between the goal-directed and habitual control systems and a *baseline responding test* to control for general task demands (e.g., response inhibition). At the beginning of each of 6 *slips-of-action* blocks, participants were shown an overview with all 6 outcomes (open boxes with fruits inside) from the first instrumental learning phase arranged in a 2 × 3 array for 10 s on the pc screen. Two of the outcomes had a red cross superimposed on them, and participants were clearly instructed that these two outcomes would from now on no longer earn points, but instead would lead to a subtraction of points if on these specific trials they continued to press the associated response key (i.e., instructed, cognitive outcome devaluation). Participants were then shown a rapid series of stimuli from the first phase (i.e., closed boxes with fruits depicted on the outside) with the instruction to press the keys to open the boxes that would lead to still-valuable outcomes ("Go trials") to gain more points, and to refrain from responding to the stimuli that would lead to devalued outcomes ("No-Go trials") to avoid losing points from their total. No trial-by-trial feedback was provided, but participants were shown their total score at the end of each block. Each of 3 blocks contained in a random order all stimuli 6 times, with each outcome being devalued twice across all blocks. Thus, participants completed in total 108 trials in the slips-of-action phase, from which the percentage responses to Go and No-Go trials could be derived. Reliance on stimulus-response habits should lead to errors (i.e., continued pressing of the response key) towards no-longer-valuable outcomes on the No-Go trials. In contrast, dominant goal-directed control should allow for selective responding towards still-valuable outcomes on the Go trials.

In the *baseline responding test*, stimuli are devalued as opposed to (consequent) outcomes/goals as in the slips-of-action test (de Wit et al., 2007; Worbe, Savulich, de Wit, Fernandez-Egea, & Robbins, 2015). Participants were instructed to withhold responses to a subset of the stimuli ("No-Go trials") while still responding to the other stimuli ("Go trials"). The baseline responding test included 3 blocks containing all stimuli 6 times, for a total of 108 baseline responding trials. The slips-of-action and baseline responding test were counterbalanced across participants. For an example of the instrumental learning paradigm, see Fig. 1 (Panel A).

### 2.2. Study 1 Procedure

Participants were tested in individual morning sessions between 09 h and 12 h. They were asked not to brush their teeth and to refrain from food, drinks, and intense physical exercise at least 2 h prior to the test phase, and none reported to have violated these directives. After arrival in the laboratory, participants read information about the study and provided written informed consent. Participants then were explained in detail the instrumental learning task and engaged in the demo training, after which the actual instrumental learning phase commenced. Next, a first saliva sample was taken right before, and a second one immediately after, the stress/control procedure. Participants started the slips-of-action and baseline test of the instrumental learning task 5 min after the end of the stress/control procedure, followed by the collection of two more saliva samples, being fully debriefed, and reimbursement. The experimental timeline can be seen in Fig. 1 (Panel B).

### 2.3. Study 1 Statistical analyses

Data were checked for non-normality using Q-Q plots and Shapiro-Wilk tests of normality. One male participant from the control group was excluded from further analyses as his baseline cortisol level was more that 3SD above the mean (i.e., 87.2 nmol/l). Thus, the final sample consisted of 71 participants. As the cortisol data were skewed, a log-transformation was performed before these data were used in subsequent analyses. Cortisol data were analyzed first with a 2(Group: stress vs. control) × 4(Time: $t_{pre\text{-}stress}$, $t_{+01}$, $t_{+20}$, $t_{+35}$) mixed ANOVA, with the latter factor being a repeated measure. To examine the influence of stress-induced cortisol reactivity, we computed the maximum increase in cortisol by subtracting the baseline level from the maximum value measured after stress, and then categorized each participant in the stress group as a cortisol responder when showing a cortisol increase equal to or larger than 1.5 nmol/l (Miller, Plessow, Kirschbaum, & Stadler, 2013) or as a cortisol non-responder when the cortisol levels increased less than 1.5 nmol/l. This resulted in a group of 25 cortisol responders and a group of 11 cortisol non-responders. Group allocation was then confirmed using a 3(ResponderGroup: cortisol responders vs. cortisol non-responders vs. controls) × 4(Time: $t_{pre\text{-}stress}$, $t_{+01}$, $t_{+20}$, $t_{+35}$) mixed ANOVA. Percentage correct responses from the instrumental learning phase were subjected to a 2(Group: stress vs. control) × 12(Block: B1-B12) mixed ANOVA, while the percentage responses made in the slips-of-action and baseline tests were analyzed with 2(Group: stress vs. control) × 2(Value: devalued vs. valuable) mixed ANOVAs. Data from the instrumental learning, slips-of-action, and baseline test phases were subsequently also examined using 3(ResponderGroup: cortisol responders vs. cortisol non-responders vs. controls) × 12(Block: B1-B12) and 3(ResponderGroup: cortisol responders vs. cortisol non-responders vs. controls) × 2(Value: devalued vs. valuable) mixed ANOVAs to specifically look at the effects of strong stress-induced cortisol responses. Whenever sphericity assumptions were violated, Greenhouse-Geisser corrected *p*-values are reported. Alpha was set at 0.05 and Bonferroni-corrected for multiple comparisons where necessary. In case of significant results, ANOVAs are supplemented with Partial Eta Squared ($\eta_p^2$) values as a measure of effect size, which represent the proportion of total variation attributable to the independent variable after partialling out the contribution of the other variables under investigation. $\eta_p^2$ values of 0.01 indicate small effects, 0.06 represent medium effects, and 0.14 constitute large effects (Fritz, Morris, & Richler, 2012).[1]

### 2.4. Study 1 Results

#### 2.4.1. Neuroendocrine stress responses

Fig. 2 shows cortisol responses to the stress/control procedure for the stress and control groups (Panel A) and cortisol responders, non-responders, and controls (Panel B). As can be seen, the stress induction procedure was successful in increasing cortisol levels in the stress group exclusively (Group * Time interaction: $F_{3,207} = 25.36$, $p < .001$, $\eta_p^2 = 0.27$). Simple effects showed that groups differed significantly in cortisol concentrations at $t_{+20}$ ($F_{1,69} = 9.38$, $p = .003$) and $t_{+35}$ ($F_{1,69} = 8.13$, $p = .006$), but not at $t_{pre\text{-}stress}$ ($F_{1,69} = 0.60$, $p = .44$) or $t_{+01}$ ($F_{1,69} = 1.04$, $p = .31$). Likewise, cortisol responders differed from cortisol non-responders and controls (ResponderGroup * Time interaction: $F_{6,204} = 36.58$, $p < .001$, $\eta_p^2 = 0.52$), with simple effects tests again confirming that cortisol responders differed significantly in cortisol concentrations from cortisol non-responders and controls at $t_{+20}$ ($p = .004$ and $p < .001$, respectively) and $t_{+35}$ ($p = .010$ and $p < .001$, respectively), but not at $t_{pre\text{-}stress}$ or $t_{+01}$ (all $ps > .50$).

#### 2.4.2. Instrumental learning performance

Instrumental learning did not differ between stress and control group (Group * Block interaction: $F_{11,759} = 0.87$, $p = .50$), and increased significantly over the 12 learning blocks (Block: $F_{11,759} = 95.20$, $p < .001$, $\eta_p^2 = 0.58$) in the absence of a main effect of Group ($F_{1,69} = 0.25$, $p = .62$). The same pattern was found for the

[1] As the effects of acute stress on memory and cognition may differ between men and women (Andreano & Cahill, 2009; Merz & Wolf, 2017; Shields et al., 2017), all analyses pertaining to the instrumental learning task in Study 1 were also repeated with sex included as an additional between-subject factor. In none of the Group or ResponderGroup analyses did sex moderate the learning performance or slips-of-action performance (no significant main or interactive effects of Sex, all $ps > .05$).

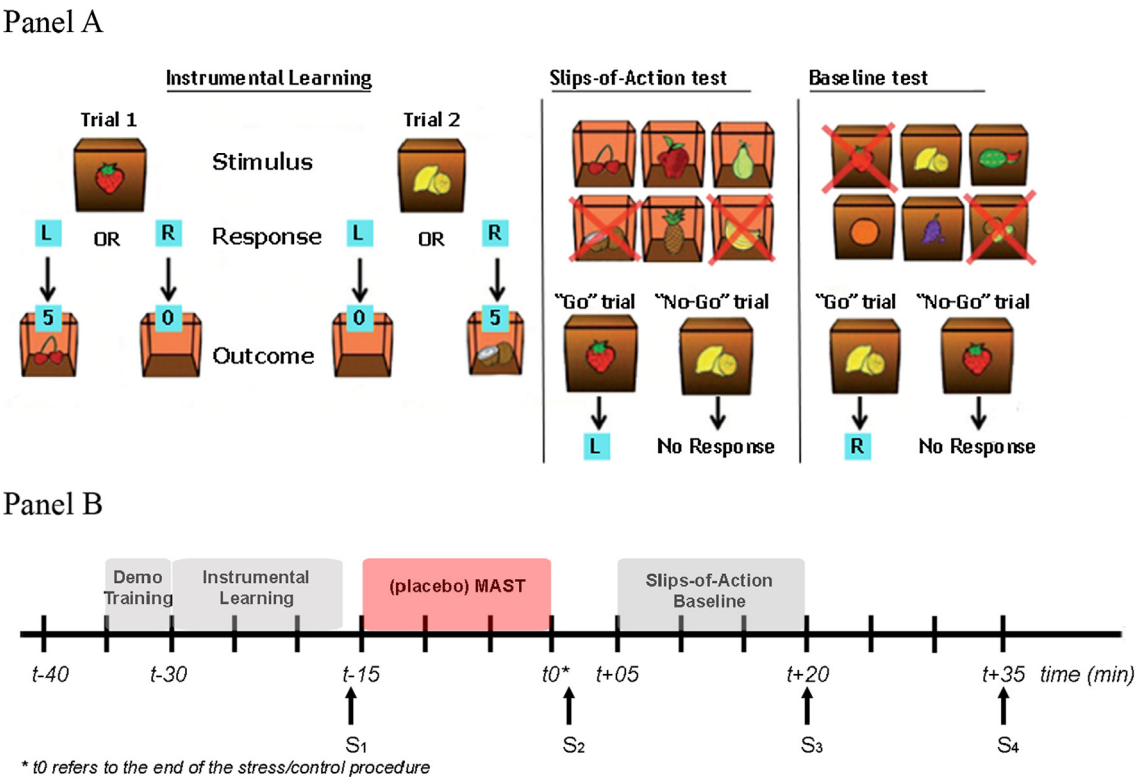


**Fig. 1.** Panel A shows an example of the original instrumental learning task used in Study 1. Panel B shows the timeline of Study 1's experimental events, with *t0* referring to end of the stress induction or control procedure and *S*s denoting times when saliva was sampled.

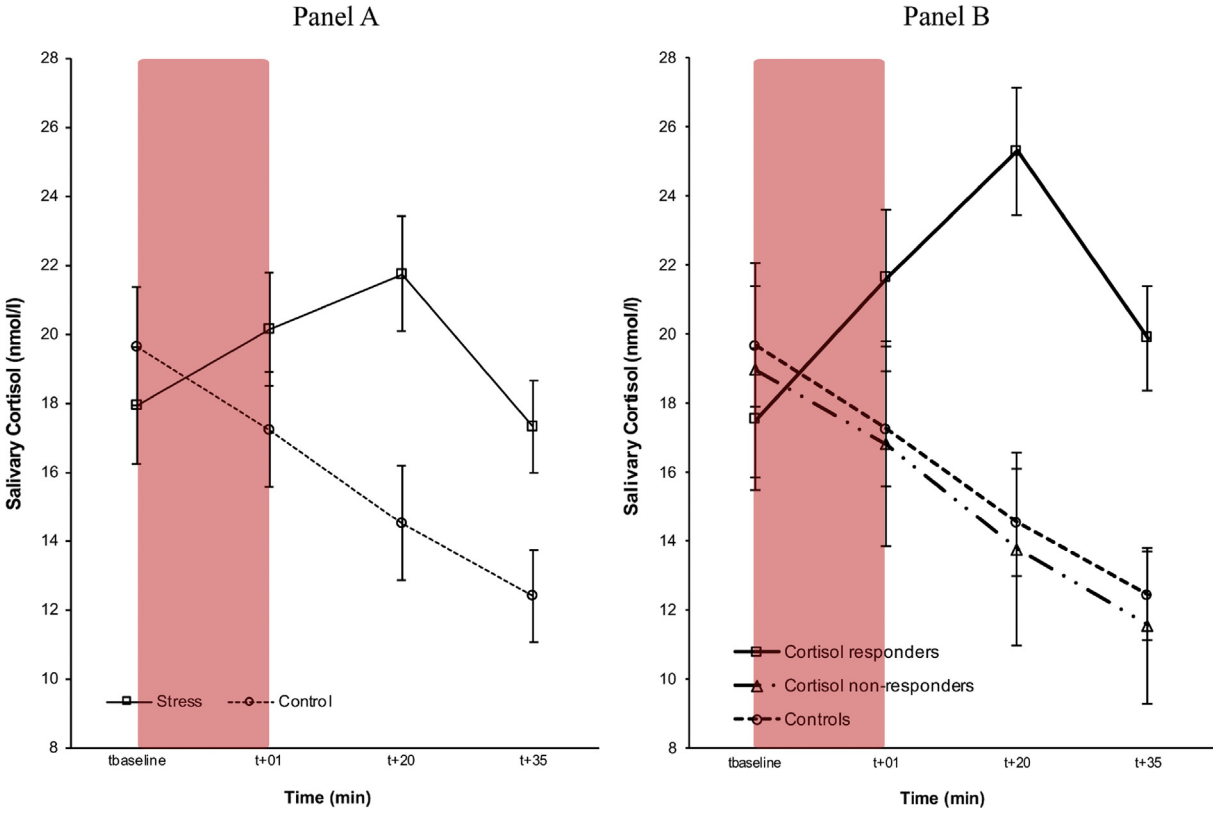


**Fig. 2.** Study 1 cortisol responses for the stress and control group (Panel A) and for the cortisol responders, cortisol non-responders, and controls separately (Panel B). The stress/control procedure is represented by the shaded area. Graphs show mean (untransformed) values ± *SE*.

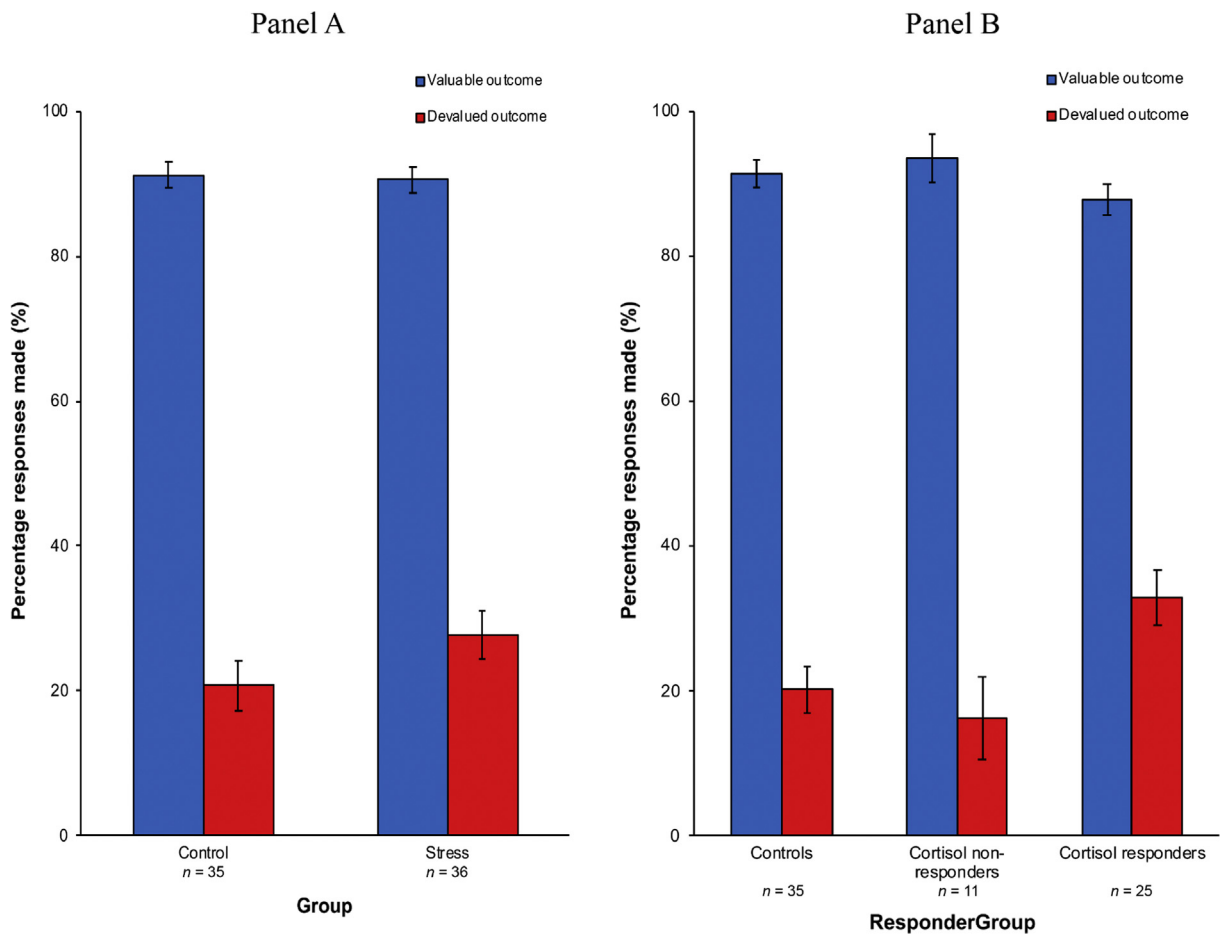


**Fig. 3.** Study 1 performance on the slips-of-action test for the stress and control group (Panel A) and for the cortisol responders, cortisol non-responders, and controls separately (Panel B). Bars show mean ( ± *SE*) percentage responses made towards still-valuable and devalued outcomes, with higher percentages of responding towards devalued outcomes indicating increased reliance on habitual behavior.

comparison between cortisol responders, cortisol non-responders and controls (ResponderGroup * Block interaction: $F_{22,748} = 0.69$, $p = .73$; Block: $F_{11,748} = 73.14$, $p < .001$, $\eta_p^2 = 0.52$; Group: $F_{2,68} = 0.35$, $p = .71$). All groups reached near-ceiling levels of accuracy already at the 8th block and remained high afterwards (e.g., Block 12: cortisol responders: 98%; cortisol non-responders: 94%; controls: 97%), indicating successful acquisition of the SRO contingencies (see Supplementary Materials, Fig. S1).

### 2.4.3. Slips-of-action and baseline test performance

Performance on the crucial slips-of-action test is shown in Fig. 3. Stress and control group unexpectedly did not differ in terms of responses made towards valuable or devalued outcomes (Group * Value: $F_{1,69} = 2.05$, $p = .16$; Group ($F_{1,69} = 2.05$, $p = .15$), with more responses made to still-valuable outcomes relative to devalued outcomes (Value: $F_{1,69} = 415.62$, $p < .001$, $\eta_p^2 = 0.86$) (see Fig. 3 Panel A). In contrast, high cortisol stress responders differed from cortisol non-responders and controls on goal-directed versus habitual behavior (ResponderGroup * Value: $F_{2,68} = 3.76$, $p = .028$, $\eta_p^2 = 0.10$; cf. Fig. 3 Panel B). Simple effects revealed that groups differed on percentage responses made towards devalued (ResponderGroup: $F_{2,68} = 4.25$, $p = .018$) but not valuable (ResponderGroup: $F_{2,68} = 1.28$, $p = .29$) outcomes. Follow-up pairwise comparisons revealed that cortisol responders exhibited stronger habitual behavior, as indicated by them making more responses to devalued outcomes than cortisol non-responders ($p = .019$) and controls ($p = .015$). Cortisol non-responders and controls did not differ in percentage responses to devalued outcomes ($p = .54$).

To control for general task characteristics (e.g., inhibitory control) of the slips-of-action test, performance on the baseline test was analyzed (see Supplementary Materials, Fig. S2). Stress and control group did not differ in baseline performance (Group * Value: $F_{1,69} = 0.35$, $p = .56$; Group: $F_{1,69} = 0.52$, $p = .47$), and displayed the expected main effect of Value ($F_{1,69} = 2481.52$, $p < .001$, $\eta_p^2 = 0.97$). The same holds true for baseline performance between cortisol responders, cortisol non-responders and controls (ResponderGroup * Value: $F_{2,68} = 1.63$, $p = .20$; ResponderGroup: $F_{2,68} = 0.72$, $p = .49$; Value: $F_{1,68} = 2097.86$, $p < .001$, $\eta_p^2 = 0.97$).

## 2.5. Summary Study 1

Study 1 found evidence that stress-induced cortisol elevations are linked to an increased reliance on habitual behavior at the expense of goal-directed behavior. That is, compared to cortisol non-responders and no-stress controls, cortisol responders displayed more responding towards cues that would lead to no-longer valuable outcomes (slips-of-action), while no differences were found for responding towards still-valuable outcomes. However, on a group level, study 1 failed to replicate the finding that stressed individuals become insensitive to the value of outcomes relative to controls (e.g., Schwabe & Wolf, 2009).

The discordance between previous findings and the results of Study 1 may be due to differences in the used outcome devaluation paradigm. Indeed, most work evidencing a stress-induced shift towards habits employed an outcome devaluation paradigm that involved instrumental learning of response-outcome associations followed by a behavioral devaluation procedure (e.g., eating to satiety), after which instrumental

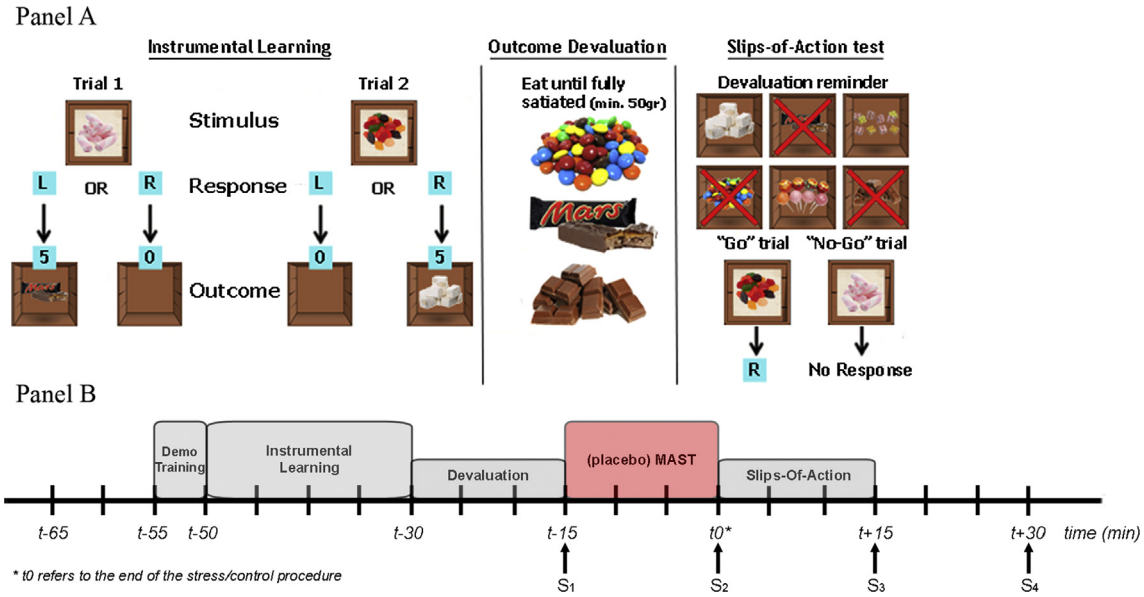


**Fig. 4.** Panel A provides an example of the sweet task version of Study 2's modified three-stage instrumental learning paradigm. Study 2's sequence of experimental events is shown in Panel B, with *t0* referring to end of the stress induction or control procedure and *Ss* denoting times when saliva was sampled.

responding was evaluated in an extinction test (e.g., Schwabe & Wolf, 2009, 2010). Here, we used explicit instructions to devalue certain outcomes and tested instrumental performance in a slips-of-action test (de Wit et al., 2007), and found no evidence for a general stress-induced shift to habitual responding. Notably, Fournier et al. (2017) recently used the same outcome devaluation paradigm by de Wit et al. (2007) as in our Study 1 to examine time-dependent effects of stress on instrumental behavior. These authors compared no-stress controls to participants who either were stressed before instrumental learning and tested for slips-of-actions in the absence of stress (24 h later) or were stressed prior to the slips-of-action phase (but not before instrumental learning 24 h earlier). Relative to the no-stress controls, only participants stressed before the slips-of-action phase were found to display a shift towards more habitual responding. Thus, using the same instructed outcome devaluation procedure (i.e., by crossing out devalued outcomes), Fournier et al. (2017) were unable to replicate that stress prior to instrumental learning shifts behavior from goal-directed to habitual control (e.g., Schwabe & Wolf, 2009). All in all, the findings by Fournier et al. (2017) and our Study 1 may be indicative of the instructed (cognitive) devaluation and subsequent slips-of-action test being less sensitive to assess shifts in goal-directed to habitual control of instrumental behavior following stress than the behavioral outcome devaluation and subsequent extinction test used in the work by Schwabe and colleagues (e.g., Schwabe & Wolf, 2009, 2010).

Study 2 was designed to directly test – via a modified instrumental learning paradigm – whether including a recognized effective behavioral devaluation procedure (i.e., eating to satiety) could increase the sensitivity of a slips-of-action test for finding stress-induced differences in the balance between goal-directed and habitual responding. Moreover, the formation of habits is said to occur when responses are frequently rewarded during associative SRO learning. Given that extensive instrumental training leads to stronger habitization (Tricomi, Balleine, & O'Doherty, 2009; for similar evidence in rodents see for example Dickinson, Balleine, Watt, Gonzalez, & Boakes, 1995), Study 2 also endeavored to increase the strength of the instrumentally learned associations by including more learning trials and by rewarding participants for learning the associations.

## 3. Study 2

### 3.1. Study 2 Method

#### 3.1.1. Participants

Sixty healthy undergraduates (24 men; 36 women) with a mean age of 23.02 years (*SD* = 3.57; *range* = 19–35) and a mean BMI of 22.12 (*SD* = 2.53; *range* = 18.1–27.2) participated in the current study. Stress and no-stress control group did not differ in age ($t_{58} = -0.36$, $p = .97$) or BMI ($t_{58} = 0.76$, $p = .45$]. We pseudo-randomly assigned 12 men and 18 women to each group. Eligibility was assessed as per Study 1. Test protocols were approved by the standing ethics committee of the Faculty of Psychology and Neuroscience, Maastricht University. All participants provided written informed consent and received a small financial reward or partial course credit in return for their participation.

#### 3.1.2. Stress vs. no-stress control procedure

Study 2's stress induction and no-stress control procedures were identical to those of Study 1 (i.e., MAST and placebo MAST; Smeets et al., 2012).

#### 3.1.3. Neuroendocrine stress responses

Salivary cortisol was collected immediately before (i.e., $t_{baseline}$) and 1, 15, and 30 min after end of the stress/control procedure (i.e., $t_{+01}$, $t_{+15}$, $t_{+30}$), and subsequently stored and analyzed as per Study 1.

#### 3.1.4. Modified instrumental learning task

We modified Study 1's instrumental learning task by including more learning trials and providing occasional food rewards to form stronger habitual responses during the learning phase, and by including a behavioral devaluation manipulation (cf. Valentin et al., 2007, Schwabe & Wolf, 2009) to more effectively devalue certain outcomes. The modified instrumental learning task comprised three stages: instrumental learning, behavioral outcome devaluation, and a slips-of-action test (see Fig. 4 Panel A).

The *modified instrumental learning stage* used instructions (earn as many points as possible) and a demo phase analogous to those of Study 1, and also included 6 to-be-learned SRO associations, each one presented twice per block of 12 trials. There were, however, 16 blocks (192 trials in total) instead of 12 to further strengthen the learned

associations. SRO instrumental learning performance was determined by calculating the correct response rate for each block. Aside from trial-by-trial feedback and showing participants' block and cumulative total scores after each block as per Study 1, we also implemented a reward incentive after blocks 4, 8, 12, and 16. Three very small pieces of food corresponding to three of the outcomes in the game were used as reward incentives. Participants were misleadingly told that if they learned the associations above a certain threshold level (which was left undefined), they would receive food rewards. In reality, all participants were given the food rewards and had to eat them independent of their learning performance.

Next, we implemented a *behavioral outcome devaluation stage* to abolish the reward value of half of the outcomes. Participants had to consume foods corresponding to 3 out of 6 outcomes until fully satiated. Participants were first given a small piece of each of the 3 to-be-devalued food outcomes, representing the minimum amount that they had to eat ( ± 50 g in total). After consuming the minimum amount, a large bowl filled with the 3 foods was put on the desk table in front of them, having first closely weighted and noted down the beginning net weight ( ± 200 g). Participants were instructed to take a seat in a comfortable position in front of a 22″ screen and were told that during the next 11½ minutes they were going to watch a compilation of funny sketches taken from the popular American TV show "Friends", during which they had to eat as much as possible without getting sick to their stomach. Lights in the lab room were dimmed as the compilation movie of Friends started. Thus, as per Watson, Wiers, Hommel, and de Wit (2014), we simulated a home environment to make participants feel more comfortable while eating as much as they could. To check for potential between-group differences in devaluation, we measured (1) the exact amount of food that was consumed by each participant, and (2) we obtained hunger ("*How hungry are you at the moment?*"; anchors: 0 = *not at all hungry* – 100 = *very hungry*) and willingness-to-eat ("*Do you feel like eating something tasty?*"; anchors: 0 = *not at all* – 100 = *very much so*) ratings before and after the outcome devaluation phase.

The third and final *slips-of-action stage* closely resembled that of the original instrumental learning paradigm by de Wit et al. (2007; cf. supra, Study 1), and assessed the relative balance between goal-directed and habitual control. Each block started with all 6 outcomes displayed in a 2 × 3 array, with the 3 food outcomes used in the behavioral outcome devaluation phase crossed out. This screen was identical for each slips-of-action test block since participants were selectively devalued by consuming to satiety foods corresponding to half of the outcomes. Thus, this screen merely served as a devaluation reminder. There were 4 blocks of 48 trials, meaning that each SRO association was probed 8 times per block. High levels of responding to devalued outcomes are indicative of dominant stimulus-response habits, while selective responding to the still-valuable outcomes only reflects goal-directed control.

Three versions of this modified instrumental learning paradigm were developed and tested in a pilot study, differing only in the type of stimulus-outcome combinations that were used. The *healthy* task version included pictures of vegetables and fruits (e.g., broccoli, cucumber, apple) as stimulus-outcome combinations. Slices of apple, orange, and banana served as food rewards in the instrumental learning phase and were used as consumables in the outcome devaluation phase. A *sweet* task version with stimulus-outcome pictures of sweets (e.g., lollipops, marshmallows, M&Ms) used pieces of milk chocolate, M&Ms, and minimars as food rewards and devalued outcomes. The third, *salty* task version employed pictures of salted snacks (e.g., pretzels, liquorish, peanuts) as stimulus-outcome combinations, and salted popcorn, crisps, and Tuc crackers as food rewards and devalued outcomes. Pilot data ($N$ = 60; 20 participants randomly assigned per task version) showed that task versions did not differ in their instrumental learning performance (both *ps* > .12 for main and interaction effect related to task version; percentage correct over final 4 blocks > .96 for all task versions) or in relative balance between goal-directed and habitual behavior in the slips-of-action phase (both *ps* > .14). Therefore, in Study 2, we allowed participants to choose beforehand whether they wanted to do the sweet or the salty task version. We excluded the healthy version as during piloting too much fruit that remained unconsumed had to be disposed of. In Study 2, 28 participants opted for the sweet and 32 for the salty version.

### 3.2. Study 2 Procedure

Testing took place between 09 h and 12 h. The same directives (e.g., no drinking or eating beforehand) as in Study 1 were given to participants. After providing informed consent, participants were familiarized with the instrumental learning task via instructions and demo training. They then completed the instrumental learning and outcome devaluation phases, after which a first saliva sample was taken. Participants were then subjected to the stress/control procedure, and immediately afterwards a second saliva sample was taken. Finally, the slips-of-action phase was carried out and two more saliva samples were obtained, followed by participants being debriefed and reimbursement. The experimental timeline of Study 2 can be seen in Fig. 4, Panel B.

### 3.3. Study 2 Statistical analyses

Data were checked for non-normality using Q-Q plots and Shapiro-Wilk tests of normality. All baseline cortisol levels fell within the normal (mean ± 3SD) range. A log-transformation was performed due to skewness of the cortisol data. Cortisol data were analyzed analogous to Study 1 (Group and ResponderGroup mixed ANOVA analyses), with 22 stressed participants categorized as cortisol responders and 8 as cortisol non-responders. For one cortisol responder in the stress group, cortisol data of $t_{+01}$ and $t_{+15}$ samples contained insufficient saliva to be analyzed and, therefore, this participant is excluded in all cortisol (but not other) analyses. Percentage correct responses of the instrumental learning phase were analyzed using 2(Group: stress vs. control) × 16(Block: B1-B16) and 3(ResponderGroup: cortisol responders vs. cortisol non-responders vs. controls) × 16(Block: B1-B16) mixed ANOVAs. Effectiveness of the devaluation procedure was assessed by calculating how much participants ate during devaluation, and by inspecting changes from pre-devaluation to post-devaluation in hunger and willingness-to-eat ratings. Amount of food eaten was analyzed using 2(Group: stress vs. control) and 3(ResponderGroup: cortisol responders vs. cortisol non-responders vs. controls) univariate ANOVAs, while changes in hunger and willingness-to-eat ratings were evaluated with 2(Group: stress vs. control) × 2(Time: pre-devaluation vs. post-devaluation) and 3(ResponderGroup: cortisol responders vs. cortisol non-responders vs. controls) × 2(Time: pre-devaluation vs. post-devaluation) mixed ANOVAs. Percentage responses made in the slips-of-action test was analyzed with 2(Group: stress vs. control) × 2(Value: devalued vs. valuable) and 3(ResponderGroup: cortisol responders vs. cortisol non-responders vs. controls) × 2(Value: devalued vs. valuable) mixed ANOVAs.[2,3] As per Study 1, Greenhouse-Geisser corrected *p*-values are reported when sphericity assumptions were violated; alpha was set at 0.05 and Bonferroni-corrected for multiple comparisons where necessary; and significant results from the ANOVAs are

[2] As per Study 1, including sex as an additional between-subject factor in the Group and ResponderGroup analyses of the learning or slips-of-action performance of Study 2 did not alter the pattern of results (no significant main or interactive effects of Sex, all *ps* > .05).

[3] Note that in the original studies by Schwabe and Wolf (2009, 2010), the effect of stress leading to more habits was restricted to analyses pertaining to the first 15-trial block of the extinction phase. We therefore included Block (1–4) of the slips-of-action phase as a repeated measure in our analyses of the data obtained via Study 2's modified instrumental learning paradigm, and found that the two- and three-way interactions involving Group and Block (*Fs* < 1.77; *ps* > .17) and ResponderGroup and Block (*Fs* < 1.39; *ps* > .24) were non-significant. Thus, all subsequently reported analyses were performed without Block included as a factor.

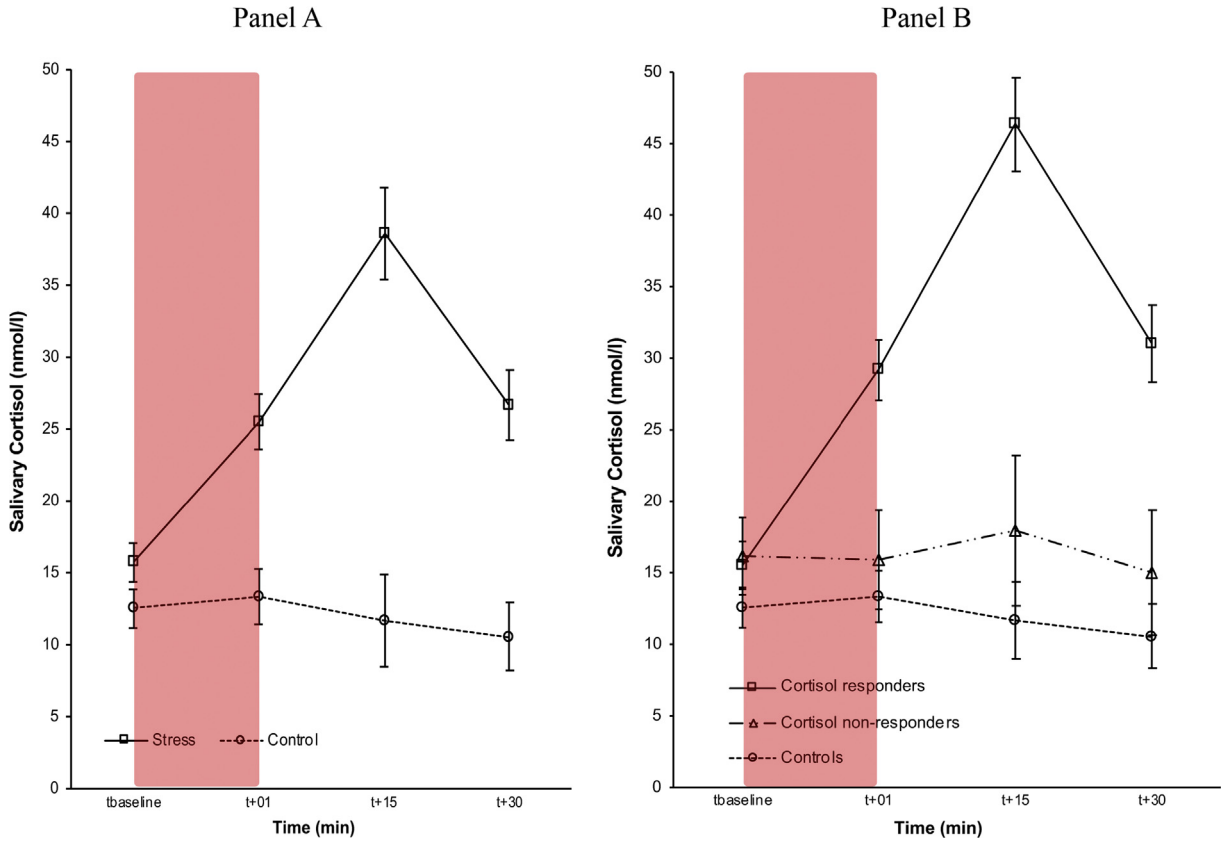


**Fig. 5.** Study 2 cortisol responses for the stress and control group (Panel A) and for the cortisol responders, cortisol non-responders, and controls separately (Panel B). The stress/control procedure is represented by the shaded area. Graphs show mean (untransformed) values ± *SE*.

supplemented with Partial Eta Squared ($\eta_p^2$) values as a measure of effect size.

### 3.4. Study 2 Results

#### 3.4.1. Neuroendocrine stress responses

Cortisol responses to the stress/control procedure can be seen in Fig. 5. Exposure to the stress procedure significantly increased cortisol levels in the stress group only (Group * Time interaction: $F_{3,171} = 26.66$, $p < .001$, $\eta_p^2 = 0.32$), with simple effects demonstrating group differences in cortisol concentrations at $t_{+01}$ ($F_{1,57} = 27.92$, $p < .001$), $t_{+15}$ ($F_{1,57} = 66.74$, $p < .001$) and $t_{+30}$ ($F_{1,57} = 46.50$, $p < .001$), but not at $t_{pre\text{-}stress}$ ($F_{1,57} = 2.49$, $p = .12$). Evidently, cortisol responders differed from cortisol non-responders and controls (ResponderGroup * Time interaction: $F_{6,168} = 23.84$, $p < .001$, $\eta_p^2 = 0.46$), with simple effects corroborating that cortisol responders differed significantly in cortisol concentrations from cortisol non-responders and controls at $t_{+01}$ ($p = .008$ and $p < .001$, respectively), $t_{+15}$ (both *ps* $< .001$), and $t_{+30}$ ($p = .002$ and $p < .001$, respectively), but not at $t_{pre\text{-}stress}$ (all *ps* $> .60$).

#### 3.4.2. Instrumental learning performance

Instrumental learning rates did not differ between stress and control group (Group * Block interaction: $F_{15,870} = 0.68$, $p = .68$), As expected, correct responses increased significantly over blocks (Block: $F_{15,870} = 64.34$, $p < .001$, $\eta_p^2 = 0.53$), without a main effect of Group ($F_{1,58} = 0.04$, $p = .84$). Instrumental learning rates also did not differ between cortisol responders, cortisol non-responders and controls (ResponderGroup * Block interaction: $F_{30,855} = 1.12$, $p = .30$; Block: $F_{15,855} = 43.73$, $p < .001$, $\eta_p^2 = 0.43$; Group: $F_{2,57} = 2.70$, $p = .08$). Near-ceiling levels of accuracy indicating successful acquisition of the SRO contingencies were observed in all groups at the end of the learning phase (Block 16: cortisol responders: 95%; cortisol non-responders: 97%; controls: 98%; see Supplementary Materials, Fig. S3).

#### 3.4.3. Effectiveness of the devaluation procedure

Stress and control group did not differ in how much food they ate during the devaluation procedure (Group: $F_{1,58} = 0.10$, $p = .76$). Hunger ratings decreased significantly as expected (Time: $F_{1,58} = 113.18$, $p < .001$, $\eta_p^2 = 0.66$), and did not differ between groups (Group * Time interaction: $F_{1,58} = 0.61$, $p = .44$; Group: $F_{1,58} = 2.15$, $p = .15$). Also, in line with our expectations, participants were less willing to eat after devaluation (Time: $F_{1,58} = 92.26$, $p < .001$, $\eta_p^2 = 0.61$), an effect that did not differ between groups (Group * Time interaction: $F_{1,58} = 0.08$, $p = .78$; Group: $F_{1,58} = 0.87$, $p = .36$). Amount of food consumed during devaluation across groups, and pre- and post-devaluation hunger and willingness-to-eat ratings can be found in Table 1.

Similar results were obtained when comparing cortisol responders, cortisol non-responders, and controls. An equal amount of food was eaten during devaluation in all groups (ResponderGroup: $F_{2,57} = 0.75$,

**Table 1**
Mean amount (*S.E.*) of food (in grams) consumed during devaluation and pre- and post-devaluation hunger and willingness-to-eat ratings (0–100) of the stress and control group in Study 2.

| | Control group (n = 30) | Stress group (n = 30) |
|---|---|---|
| Amount of food eaten | 112.93 (7.87) | 109.67 (6.94) |
| Pre-devaluation hunger | 55.10 (4.14) | 64.03 (3.96) |
| Post-devaluation hunger | 20.50 (3.38) | 23.93 (3.99) |
| Pre-devaluation willingness-to-eat | 65.10 (3.28) | 68.67 (4.49) |
| Post-devaluation willingness-to-eat | 29.20 (4.42) | 34.83 (4.97) |

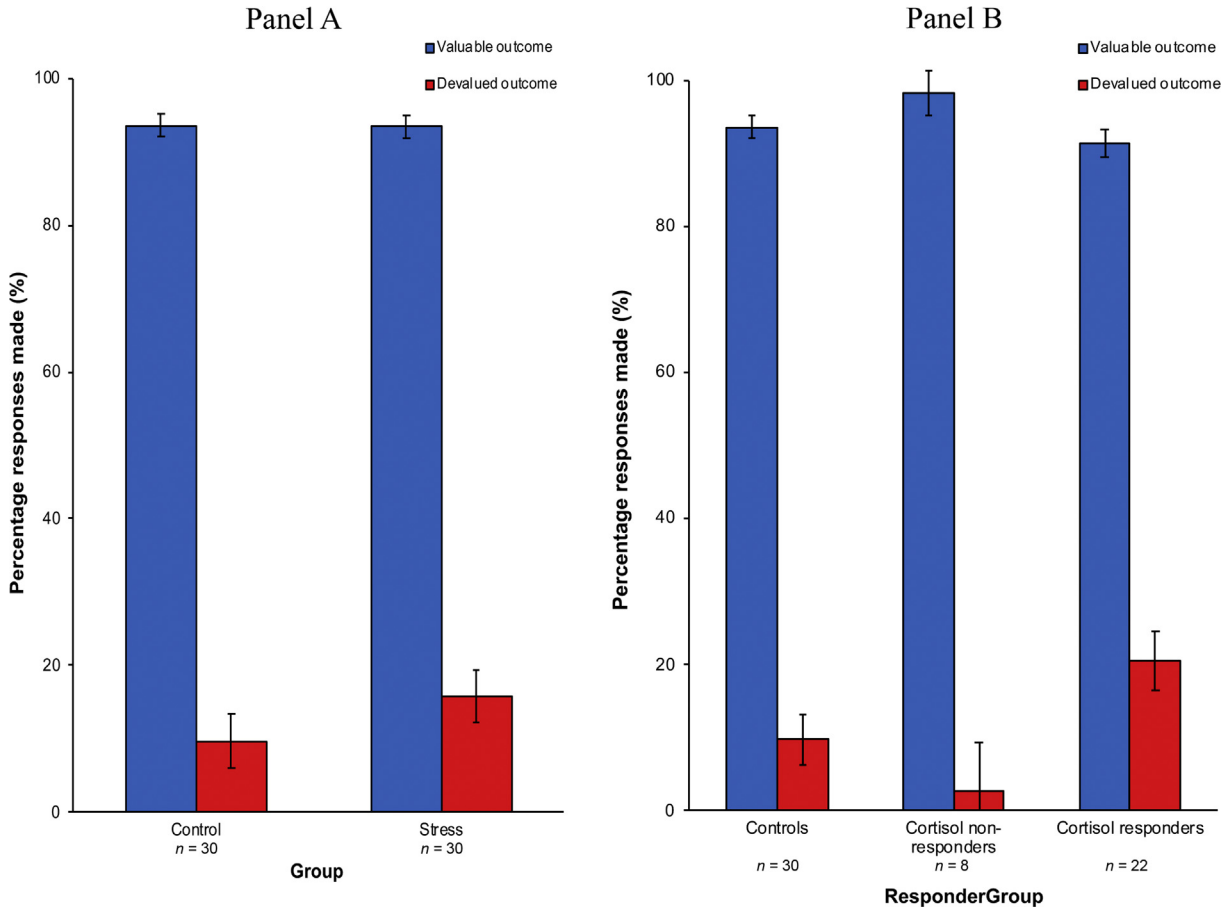


**Fig. 6.** Study 2 performance on the slips-of-action test for the stress and control group (Panel A) and for the cortisol responders, cortisol non-responders, and controls separately (Panel B). Bars show mean ( ± *SE*) percentage responses to still-valuable and devalued outcomes.

$p$ = .48). Hunger did not differ between ResponderGroups (Group * Time interaction: $F_{2,57}$ = 1.13, $p$ = .33; Group: $F_{2,57}$ = 1.60, $p$ = .21), but decreased significantly over time (Time: $F_{1,57}$ = 78.44, $p$ < .001, $\eta_p^2$ = 0.58). Likewise, willingness-to-eat declined similarly across groups (Group * Time interaction: $F_{2,57}$ = 1.48, $p$ = .24; Group: $F_{2,57}$ = 1.81, $p$ = .17; Time: $F_{1,57}$ = 57.25, $p$ < .001, $\eta_p^2$ = 0.50).

#### 3.4.4. Slips-of-action performance

Fig. 6 displays participants' performance on the slips-of-action test. Replicating Study 1, stress and control group did not differ in terms of balanced responding to still-valuable and devalued outcomes (Group * Value: $F_{1,58}$ = 0.87, $p$ = .36; Group ($F_{1,58}$ = 2.07, $p$ = .16), with more responses made to the still-valuable outcomes relative to devalued outcomes (Value: $F_{1,58}$ = 571.39, $p$ < .001, $\eta_p^2$ = 0.91) (see Fig. 6 Panel A). Also, in line with our findings of Study 1, high cortisol stress responders in Study 2 differed from cortisol non-responders and controls on goal-directed versus habitual behavior (ResponderGroup * Value: $F_{2,57}$ = 3.30, $p$ = .044, $\eta_p^2$ = 0.10). Simple effects revealed that groups differed on percentage responses made towards devalued (ResponderGroup: $F_{2,57}$ = 3.37, $p$ = .042) but not still-valuable (ResponderGroup: $F_{2,57}$ = 1.82, $p$ = .17) outcomes (see Fig. 6 Panel B). Follow-up pairwise comparisons revealed that cortisol responders exhibited stronger habitual behavior, as indicated by them making more responses to devalued outcomes than cortisol non-responders ($p$ = .026) and controls ($p$ = .047). Cortisol non-responders and controls did not differ on responses to devalued outcomes ($p$ = .36).

### 3.5. Summary Study 2

Using a modified instrumental learning paradigm that capitalized on more strongly formed habits and a true behavioral devaluation procedure, Study 2 basically replicated the findings of Study 1. That is, notwithstanding robust cortisol responses to the stressor and significant decreases in willingness-to-eat and hunger ratings, selective behavioral outcome devaluation in Study 2 did not lead stressed participants to differ from no-stress control participants in their use of goal-directed versus habitual control in the slips-of-action task. Also, Study 2 replicated the finding that cortisol responding stressed participants made more slips-of-action errors than both cortisol non-responders and controls, indicating that cortisol responses are required for stress-induced shifting towards habits to occur (cf. Schwabe & Wolf, 2010; Schwabe et al., 2011).

## 4. Discussion

The current studies further examined the robustness of the finding that stress provokes habitual behavior. In doing so, we employed an outcome devaluation paradigm that is different from the previously used instrumental learning task that consisted of instrumental reward learning, behavioral outcome devaluation, and a crucial extinction test to distinguish goal-directed from habitual control over behavior (e.g., Schwabe & Wolf, 2009, 2010; Valentin et al., 2007). Specifically, we assessed instrumental control of behavior using the slips-of-action paradigm originally developed by de Wit et al. (2007), which has proven successful in discriminating the balance between goal-directed and habitual responding in various experimental contexts and

populations (e.g., Chen et al., 2017; de Wit, Barker, Dickinson, & Cools, 2011, 2012, 2014; Delorme et al., 2016; Fournier et al., 2017; Gillan, et al., 2011; Worbe et al., 2015; for review of the different paradigms see Watson & de Wit, 2018). The main results can be summarized as follows. Both Study 1 and Study 2 found that participants displaying stress-induced cortisol reactivity made more errors to devalued outcomes in the slips-of-action phase – indicating prominent habitual responding – relative to stress-exposed cortisol non-responders and no-stress controls. Both studies, however, failed to replicate that stress overall, i.e., independent of cortisol reactivity, shifted behavior from goal-directed to habitual control.

The importance of individual differences in cortisol responses as a driving mechanism behind stress-induced alterations in the engagement of habits versus goal-directed actions was demonstrated in the current studies. Only in participants showing a clear-cut cortisol response larger than 1.5 nmol/l (Miller et al., 2013) did we find that stress led to preferential habitual responses. This accords well with observations that higher stress-induced cortisol responses were associated with increased habitual responding (e.g., Otto et al., 2013; Schwabe & Wolf, 2010; Schwabe et al., 2011). Also consistent with this conclusion are the results of a recent study by Goldfarb and colleagues, who examined the influence of acute stress applied either post-learning (Goldfarb, Mendelevich, & Phelps, 2017, Experiment 1) or pre-retrieval (Goldfarb et al., 2017, Experiment 2) on the expression of learned stimulus-response associations. Results showed that neither stress after learning nor stress before retrieval affected the expression of habitual stimulus-response memory. However, these authors did find that differences in stress-induced cortisol reactivity post-learning were associated with variability in initial stimulus-response learning.

There may be various reasons as to why some studies have found an unambiguous effect of stress on instrumental learning and others only under specific conditions (e.g., Fournier et al., 2017; Goldfarb et al., 2017; Otto et al., 2013, Radenbach et al., 2015). One might speculate that this has to do with the variability in the employed instrumental learning paradigm, with the most convincing evidence of stress stimulating habits coming from studies using a behavioral devaluation manipulation followed by an extinction test probing for previously learned stimulus-response associations (e.g., Schwabe & Wolf, 2009, 2010) or a probabilistic classification learning task (e.g., Schwabe et al., 2013; Wirz, Wacker, Felten, Reuter, & Schwabe, 2017). Less clear evidence was found in studies that used a sequential decision task (Otto et al., 2013; Radenbach et al., 2015) or an outcome devaluation and slips-of-action paradigm (Fournier et al., 2017). That the outcome devaluation and slips-of-action paradigm by de Wit et al. (2007) used in the current studies is seemingly less sensitive to pick up on subtle differences in the balance between goal-directed and habitual behavior resulting from stress exposure is surprising given the successful differentiation found in various clinical populations and following certain pharmacological manipulations (cf. supra). The slips-of-action paradigm of de Wit et al. (2007) has also shown convergent validity with the sequential decision making task (Sjoerds, et al., 2016), which in turn has shown to correlate significantly with an outcome devaluation paradigm (Friedel et al., 2014). Study 2 showed that more extensive training did not lead to a stronger overall effect of stress on habitual behavior in the slips-of-action phase. While this contradicts earlier rodent (e.g., Dickinson et al., 1995) and at least one human (Tricomi et al., 2009) study, de Wit et al. (in press) recently reported five independent studies that all showed no evidence of extensive (over)training leading to stronger habits. Moreover, even though the behavioral outcome devaluation (i.e., having participants eat until satiety) seemed to be very effective, as evidenced by descriptively even fewer slips-of-action in Study 2 compared with Study 1 that included an instructed devaluation procedure, this behavioral outcome devaluation also did not result in a stronger effect of stress on habitual behavior. All in all, this suggests that an outcome devaluation paradigm that not only employs a behavioral devaluation procedure but also tests for habits in a subsequent extinction test may be needed to provide a sensitive measure of how acute stress affects instrumental learning.

Another reason for the discrepant findings might be the diverse ways in which stress was elicited and their potential to elicit strong cortisol responses as, for example, it has been suggested that both low and high levels of glucocorticoids can interfere in an inverted-U shaped manner with dorsolateral prefrontal cortex dependent cognitive functioning like goal-directed behavior (2007; Lupien, Gillin, & Hauger, 1999). The studies by Schwabe and co-workers (e.g., Schwabe & Wolf, 2009, 2010; Schwabe et al., 2013) demonstrating clear effects of stress on the preference to express habitual behaviors mostly used the Socially Evaluated Cold Pressor Test (SECPT; Schwabe, Haddad, & Schachinger, 2008), a stressor that has both physical and psychosocial elements and is deemed more effective than the traditional Cold Pressor Test used in the Goldfarb et al. (2017) and Otto et al. (2013) studies that found equivocal evidence for stress prompting habits. The current studies used the Maastricht Acute Stress Test (MAST; Smeets et al., 2012), which also involves psychosocial and physical stress components but is longer in duration than the SECPT and leads to large cortisol increases (see for other validation studies Quaedflieg et al., 2017; Shilton et al., 2017). Nevertheless, the current studies found evidence for more habitual behavior only for those participants displaying a cortisol response larger than 1.5 nmol/l. Note that although such cortisol responses were present in the large majority of participants in both studies, no significant overall effect of stress on habits was found. Finally, the studies by Fournier et al. (2017), Radenbach et al. (2015), and Wirz et al. (2017) employed the Trier Social Stress Test (TSST; Kirschbaum, Pirke, & Hellhammer, 1993), the most-often used and undoubtedly effective psychosocial stress test. While Wirz et al. (2017) found the anticipated effect of stress prompting habits, the Radenbach et al. (2015) and Fournier et al. (2017) studies were indeterminate. Thus, there seems to be no consistent relation between stressor type and the strength of the finding that stress provokes habitual behavior.

Interestingly, in the current studies the magnitude of the cortisol responses to the MAST differed substantially between Study 1 and Study 2, with Study 1 yielding smaller cortisol increases within the stress group than is typically obtained in our lab (e.g., Meyer, Smeets, Giesbrecht, Quaedflieg, & Merckelbach, 2013; Quaedflieg et al., 2017; Smeets et al., 2012) and Study 2 in contrast resulting in higher-than-usual cortisol increases. We can only speculate why this was the case, as elements that may lead to observable anticipatory stress reactions (e.g., timing of cortisol sampling relative to instructions about the upcoming stressor) and the stress manipulation itself (i.e., the MAST) were kept identical across studies. Also, there were no meaningful differences in how many men were in the stress groups (Study 1: 13; Study 2: 12), and while 30 out of 52 women in Study 1 were on oral contraceptives (of which 16 were in the stress group and 14 in the control group), in Study 2 only women taking oral contraceptives were included. As the use of oral contraceptives generally leads to reduced cortisol responses (e.g., Kirschbaum, Kudielka, Gaab, Schommer, & Hellhammer, 1999), it is unlikely that differences in oral contraceptive use contributed to the observed differences in cortisol responses between the current studies. One potential reason for the amplified cortisol responses in Study 2 is that in modifying the instrumental learning task we offered food rewards after certain learning blocks (cf. supra) and in the devaluation phase participants also consumed food. Dietary energy supply levels are known to regulate cortisol stress responses, and high glucose levels in particular lead to more pronounced cortisol increases to stress (e.g., Gonzalez-Bono, Rohleder, Hellhammer, Salvador, & Kirschbaum, 2002). Thus, in Study 2 (but not Study 1) participants consumed food before engaging in the stress test, which may have led to the observed higher cortisol responses in Study 2.

Several studies have sought to elucidate the mechanisms by which stress shifts behavior to become more dependent on the habit system. Neuroimaging studies demonstrated that stress reduces the amygdala-hippocampus connectivity while increasing the connectivity between

the amygdala and the dorsal striatum (e.g., Schwabe et al., 2013, Wirz et al., 2017), suggesting a pivotal role of noradrenergic arousal in the (basolateral) amygdala for the stress-induced shift toward habitual control of behavior. This is corroborated by pharmacological studies showing that noradrenergic arousal is necessary for cortisol to shift behavior towards habitual control (Schwabe, Tegenthoff, Höffken, & Wolf, 2010), and that blocking noradrenergic arousal via administration of the beta-adrenergic antagonist propranolol abolishes the stress-induced shift to habitual control (Schwabe et al., 2011). The crucial role of glucocorticoids in modulating goal-directed and habitual learning is supported by studies on the involvement of the cortisol-binding mineralocorticoid receptor. For example, blocking the mineralocorticoid receptor prevented enhanced stress-induced stimulus-response learning in healthy men (Vogel et al., 2017; see also Schwabe et al., 2013). In addition, a recent study showed that rats injected with glucocorticoids in the dorsolateral striatum following training in finding rewards in a cross-maze task were more efficient (i.e., faster) at learning stimulus-response associations (Siller-Perez, Serafin, Prado-Alcala, Roozendaal, & Quirarte, 2017). In summary, although future studies are needed to draw firm conclusions, it is likely that interactive effects of stress-induced cortisol reactivity and noradrenergic arousal in the basolateral amygdala are the key switch in rendering behavior more habitual rather than engaging in a more flexible but cognitively demanding goal-directed approach.

A few limitations of the current studies need to be acknowledged. First, we did not assess (nor)adrenergic activity (e.g., via salivary alpha-amylase) and thus cannot ascertain whether cortisol alone, or cortisol in conjunction with noradrenergic activity, is responsible for the observed effects. This latter hypothesis seems more likely given the currently available evidence coming from a pharmacological study that found noradrenergic arousal to be required for cortisol to lead to habitual behavior (Schwabe, Tegenthoff, et al., 2010) and from a corroborative study indicating that blocking noradrenergic arousal eliminates the stress-induced shift to habits (Schwabe et al., 2011). Second, we also did not assess subjectively experienced distress to the stress or control procedure. While subjective distress and neuroendocrine measures of stress such as cortisol often disagree (e.g., Diemer, 2017), it cannot be excluded that high levels of subjective distress among the cortisol responders are primarily responsible for the observed effects on habitual responding. Third, comparable to most studies examining the effect of stress on instrumental behavior, the current studies relied on samples of healthy undergraduate students. While employing this type of sample has certain advantages such as being a rather homogenous group in terms of age and educational background, it may also not translate directly to clinical populations. This may be important given that while two contemporary studies revealed that whereas obese participants behaved habitual (i.e., they maintained responding for food rewards after being satiated; Horstmann et al., 2015; Janssen, et al., 2017), neither obese participants (Dietrich, de Wit, & Horstmann, 2016; Watson, Wiers, Hommel, Gerdes, & de Wit, 2017) nor anorectic patients (Godier, et al., 2016) displayed increased responding toward devalued outcomes in a slips-of-action paradigm. Finally, habits are developed more successfully and are more resistant to extinction when rewards are provided on a partial (interval) reinforcement schedule (Dickinson, 1985). The instrumental learning paradigm employed in the current studies used a continuous reinforcement schedule in that each correct response during instrumental learning was rewarded with an outcome and points, while that of Schwabe and Wolf (2009, 2010) used partial reinforcement. Hypothetically, the difference in how compelling stress and stress-induced cortisol responses affect the expression of habits between the current studies and those of Schwabe and colleagues may be explained by differences in reinforcement schedules during instrumental training.

Taken together, the current studies in conjunction with previous work (e.g., Schwabe et al., 2011) demonstrate that cortisol reactivity plays a prominent role in provoking habitual behavior following exposure to an acute stressful situation. Such moving away from goal-directed behavioral strategies under stress can be seen as adaptive since cognitively demanding, effortful processes are superfluous in times when all energy should be directed at coping with the stressful situation. Certainly, reverting to old habits can be deemed beneficial in most stressful situations as relying on previously learned automatic behavior (habits) is important for being able to successfully adjust to new or varying environmental demands, and may safeguard the organism from a stressful and potentially hazardous situation.

## 5. Funding

This work was supported by the Netherlands Organization for Scientific Research (Nederlandse Organisatie voor Wetenschappelijk Onderzoek, NWO) to Dr. Tom Smeets [grant number 452-14-003] and Dr. Conny Quaedflieg [grant number 446-15-003]. NWO had no further role in the study design; in the collection, analysis and interpretation of the data; in the writing of the report; and in the decision to submit the paper for publication.

## Conflict of interest

None.

## Acknowledgements

We are especially thankful to Kemala Cut Nurul, Sylwia Kaduk, Nassim Sedaghat, and Marlies van Nieuwkoop for their help in collecting the data. We also thank Michiel Vestjens for his invaluable help in programming the instrumental learning task.

## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.bandc.2018.05.005.

## References

Andreano, J. M., & Cahill, L. (2009). Sex influences on the neurobiology of learning and memory. *Learning & Memory, 16*, 248–266.
Chen, J., Liang, J., Lin, X., Zhang, Y., Zhang, Y., Liu, L., et al. (2017). Sleep deprivation promotes habitual control over goal-directed control: Behavioral and neuroimaging evidence. *Journal of Neuroscience, 37*, 11979–11992.
Dehouwer, J., Tanaka, A., Moors, A., & Tibboel, H. (2018). Kicking the habit: Why evidence for habits in humans might be overestimated. *Motivation Science, 4*, 50–59.
de Kloet, E. R., Joels, M., & Holsboer, F. (2005). Stress and the brain: From adaptation to disease. *Nature Reviews Neuroscience, 6*, 463–475.
de Quervain, D., Schwabe, L., & Roozendaal, B. (2017). Stress, glucocorticoids and memory: Implications for treating fear-related disorders. *Nature Reviews Neuroscience, 18*, 7–19.
de Wit, S., Barker, R. A., Dickinson, A. D., & Cools, R. (2011). Habitual versus goal-directed action control in Parkinson's disease. *Journal of Cognitive Neuroscience, 23*, 1218–1229.
de Wit, S., Kindt, M., Knot, S. L., Verhoeven, A. A. C., Robbins, T. W., Gasull-Camos, J., et al. (in press). Shifting the balance between goals and habits: Five failures in experimental habit induction. Journal of Experimental Psychology: General.
de Wit, S., Niry, D., Wariyar, R., Aitken, M. R. F., & Dickinson, A. (2007). Stimulus-outcome interactions during instrumental discrimination learning by rats and humans. *Journal of Experimental Psychology. Animal Behavior Processes, 33*, 1–11.
de Wit, S., Standing, H. R., DeVito, E. E., Robinson, O. J., Ridderinkhof, K. R., Robbins, T. W., et al. (2012). Reliance on habits at the expense of goal-directed control following dopamine precursor depletion. *Psychopharmacology (Berl), 219*, 621–631.
de Wit, S., van de Vijver, I., & Ridderinkhof, K. R. (2014). Impaired acquisition of goal-directed action in healthy aging. *Cognitive, Affective, & Behavioral Neuroscience, 14*, 647–658.
Delorme, C., Salvador, A., Valabregue, R., Roze, E., Palminteri, S., Vidailhet, M., et al. (2016). Enhanced habit formation in Gilles de la Tourette syndrome. *Brain, 139*, 605–615.
Dickinson, A. (1985). Actions and habits: The development of behavioural autonomy. *Philosophical Transactions of the Royal Society of London. Series B, 308*, 67–78.
Dickinson, A., Balleine, B. W., Watt, A., Gonzalez, F., & Boakes, R. (1995). Motivational control after extended instrumental training. *Learning & Behavior, 23*, 197–206.
Diemer, J. (2017). Distress = stress? Disentangling the different components of emotional experience. *Psychoneuroendocrinology, 82*, 187–188.

Dietrich, A., de Wit, S., & Horstmann, A. (2016). General habit propensity relates to the sensation seeking subdomain of impulsivity but not obesity. *Frontiers in Behavioral Neuroscience, 10*, 213.
Fournier, M., d'Arripe-Longueville, F., & Radel, R. (2017). Effects of psychosocial stress on the goal-directed and habit memory systems during learning and later execution. *Psychoneuroendocrinology, 77*, 275–283.
Friedel, E., Koch, S. P., Wendt, J., Heinz, A., Deserno, L., & Schlagenhauf, F. (2014). Devaluation and sequential decisions: Linking goal-directed and model-based behavior. *Frontiers in Human Neuroscience, 8*, 587.
Fritz, C. O., Morris, P. E., & Richler, J. J. (2012). Effect size estimates: Current use, calculations, and interpretation. *Journal of Experimental Psychology: General, 141*, 2–18.
Gillan, C. M., Papmeyer, M., Morein-Zamir, S., Sahakian, B. J., Fineberg, M. A., Robbins, T. W., et al. (2011). Disruption in the balance between goal-directed behavior and habit learning in obsessive-compulsive disorder. *American Journal of Psychiatry, 168*, 718–726.
Godier, L. R., de Wit, S., Pinto, A., Steinglass, J. E., Greene, A. L., Scaife, J., et al. (2016). An investigation of habit learning in anorexia nervosa. *Psychiatry Research, 244*, 214–222.
Goldfarb, E. V., Mendelevich, Y., & Phelps, E. A. (2017). Acute stress time-dependently modulates multiple memory systems. *Journal of Cognitive Neuroscience, 29*, 1877–1894.
Gonzalez-Bono, E., Rohleder, N., Hellhammer, D. H., Salvador, A., & Kirschbaum, C. (2002). Glucose but not protein or fat load amplifies the cortisol response to psychosocial stress. *Hormones and Behavior, 41*, 328–333.
Horstmann, A., Dietrich, A., Mathar, D., Possel, M., Villringer, A., & Neumann, J. (2015). Slave to habit? Obesity is associated with decreased behavioural sensitivity to reward devaluation. *Appetite, 87*, 175–183.
Janssen, L. K., Duif, I., van Loon, I., Wegman, J., de Vries, J. H. M., Cools, R., et al. (2017). Loss of lateral prefrontal cortex control in food-directed attention and goal-directed food choice in obesity. *NeuroImage, 146*, 148–156.
Kirschbaum, C., Kudielka, B. M., Gaab, J., Schommer, N. C., & Hellhammer, D. H. (1999). Impact of gender, menstrual cycle phase, and oral contraceptives on the activity of the hypothalamic-pituitary-adrenal axis. *Psychosomatic Medicine, 61*, 154–162.
Kirschbaum, C., Pirke, K.-M., & Hellhammer, D. H. (1993). The 'Trier Social Stress Test': A tool for investigating psychobiological stress responses in a laboratory setting. *Neuropsychobiology, 28*, 76–81.
Lupien, S. J., Gillin, C. J., & Hauger, R. L. (1999). Working memory is more sensitive than declarative memory to the acute effects of corticosteroids: A dose-response study in humans. *Behavioral Neuroscience, 113*, 420–430.
Lupien, S. J., Maheu, F., Tu, M., Fiocco, A., & Schramek, T. E. (2007). The effects of stress and stress hormones on human cognition: Implications for the field of brain and cognition. *Brain and Cognition, 65*, 209–237.
McEwen, B. S. (1998). Stress, adaptation, and disease: Allostasis and allostatic load. *Annals of the New York Academy of Sciences, 840*, 33–44.
McEwen, B. S. (2008). Central effects of stress hormones in health and disease: Understanding the protective and damaging effects of stress and stress mediators. *European Journal of Pharmacology, 583*, 174–185.
Merz, C. J., & Wolf, O. T. (2017). Sex differences in stress effects on emotional learning. *Journal of Neuroscience, 95*, 93–105.
Meyer, T., Smeets, T., Giesbrecht, T., Quaedflieg, C. W. E. M., & Merckelbach, H. (2013). Acute stress differentially affects spatial configuration learning in high and low cortisol responding healthy adults. *European Journal of Psychotraumatology, 4*, 19854.
Miller, R., Plessow, F., Kirschbaum, C., & Stadler, T. (2013). Classification criteria for distinguishing cortisol responders to psychological stress: Evaluation of salivary cortisol pulse detection in panel designs. *Psychosomatic Medicine, 75*, 832–840.
O'Doherty, J. P., Cockburn, J., & Pauli, W. M. (2017). Learning, reward, and decision making. *Annual Review of Psychology, 68*, 73–100.
Otto, A. R., Raio, C. M., Chiang, A., Phelps, E. A., & Daw, N. D. (2013). Working-memory capacity protects model-based learning from stress. *Proceedings of the National academy of Sciences of the United States of America, 110*, 20941–20946.
Quaedflieg, C. W. E. M., Meyer, T., van Ruitenbeek, P., & Smeets, T. (2017). Examining habituation and sensitization across repetitive laboratory stress inductions using the MAST. *Psychoneuroendocrinology, 77*, 175–181.
Radenbach, C., Reiter, A. M., Engert, V., Sjoerds, Z., Villringer, A., Heinze, H. J., et al. (2015). The interaction of acute and chronic stress impairs model-based behavioral control. *Psychoneuroendocrinology, 53*, 268–280.
Roozendaal, B., & McGaugh, J. L. (2011). Memory modulation. *Behavioral Neuroscience, 125*, 797–824.
Schwabe, L., Haddad, L., & Schachinger, H. (2008). HPA axis activation by a socially evaluated cold pressor test. *Psychoneuroendocrinology, 33*, 890–895.
Schwabe, L., Höffken, O., Tegenthoff, M., & Wolf, O. T. (2011). Preventing the stress-induced shift from goal-directed to habit action with a beta-adrenergic antagonist. *Journal of Neuroscience, 31*, 17317–17325.
Schwabe, L., Tegenthoff, M., Höffken, O., & Wolf, O. T. (2010). Concurrent glucocorticoid and noradrenergic activity shifts instrumental behavior from goal-directed to habitual control. *Journal of Neuroscience, 20*, 8190–8196.
Schwabe, L., Tegenthoff, M., Höffken, O., & Wolf, O. T. (2013). Mineralocorticoid receptor blockade prevents stress-induced modulation of multiple memory systems in the human brain. *Biological Psychiatry, 74*, 801–808.
Schwabe, L., & Wolf, O. T. (2009). Stress prompts habit behavior in humans. *Journal of Neuroscience, 29*, 7191–7198.
Schwabe, L., & Wolf, O. T. (2010). Socially evaluated cold pressor stress after instrumental learning favors habits over goal-directed action. *Psychoneuroendocrinology, 35*, 977–986.
Schwabe, L., & Wolf, O. T. (2012). Stress modulates the engagement of multiple memory systems in classification learning. *Journal of Neuroscience, 32*, 11042–11049.
Schwabe, L., & Wolf, O. T. (2013). Stress and multiple memory systems: From 'thinking' to 'doing'. *Trends in Cognitive Sciences, 17*, 60–68.
Schwabe, L., Wolf, O. T., & Oitzl, M. S. (2010). Memory formation under stress: Quantity and quality. *Neuroscience and Biobehavioral Reviews, 34*, 584–591.
Shields, G. S., Sazma, M. A., McCullough, A. M., & Yonelinas, A. P. (2017). The effects of acute stress on episodic memory: A meta-analysis and integrative review. *Psychological Bulletin, 143*, 636–675.
Shilton, A. L., Laycock, R., & Crewther, S. G. (2017). The Maastricht Acute Stress Test (MAST): Physiological and subjective responses in anticipation, and post-stress. *Frontiers in Psychology, 8*, 567.
Siller-Perez, C., Serafin, N., Prado-Alcala, R. A., Roozendaal, B., & Quirarte, G. L. (2017). Glucocorticoid administration into the dorsolateral but not dorsomedial striatum accelerates the shift from a spatial toward procedural memory. *Neurobiology of Learning and Memory, 141*, 124–133.
Sjoerds, Z., Dietrich, A., Deserno, L., de Wit, S., Villringer, A., Heinze, H. J., et al. (2016). Slips of action and sequential decisions: A cross-validation study of tasks assessing habitual and goal-directed action control. *Frontiers in Behavioral Neuroscience, 10*, 234.
Smeets, T., Cornelisse, S., Quaedflieg, C. W. E. M., Meyer, T., Jelicic, M., & Merckelbach, H. (2012). Introducing the Maastricht Acute Stress Test (MAST): A quick and non-invasive approach to elicit robust autonomic and glucocorticoid stress responses. *Psychoneuroendocrinology, 37*, 1998–2008.
Smeets, T., Otgaar, H., Candel, I., & Wolf, O. T. (2008). True or false? Memory is differentially affected by stress-induced cortisol elevations and sympathetic activity at consolidation and retrieval. *Psychoneuroendocrinology, 33*, 1378–1386.
Tricomi, E., Balleine, B. W., & O'Doherty, J. P. (2009). A specific role for posterior dorsolateral striatum in human habit learning. *European Journal of Neuroscience, 29*, 2225–2232.
Ulrich-Lai, Y. M., & Herman, J. P. (2009). Neural regulation of endocrine and autonomic stress responses. *Nature Reviews Neuroscience, 10*, 397–409.
Valentin, V. V., Dickinson, A., & O'Doherty, J. P. (2007). Determining the neural substrates of goal-directed learning in the human brain. *Journal of Neuroscience, 27*, 4019–4026.
Vogel, S., Klumpers, F., Schroder, T. N., Oplaat, K. T., Krugers, H. J., Oitzl, M. S., et al. (2017). Stress induces a shift towards striatum-dependent stimulus-response learning via the mineralocorticoid receptor. *Neuropsychopharmacology, 42*, 1262–1271.
Watson, P., & de Wit, S. (2018). Current limits of experimental research into habits and future directions. *Current Opinion in Behavioral Sciences, 20*, 33–39.
Watson, P., Wiers, R. W., Hommel, B., & de Wit, S. (2014). Working for food you don't desire. Cues interfere with goal-directed food-seeking. *Appetite, 79*, 139–148.
Watson, P., Wiers, R. W., Hommel, B., Gerdes, V. E. A., & de Wit, S. (2017). Stimulus control over action for food in obese versus healthy-weight individuals. *Frontiers in Psychology, 8*, 580.
Wirz, L., Bogdanova, M., & Schwabe, L. (2018). Habits under stress: Mechanistic insights across different types of learning. *Current Opinion in Behavioral Sciences, 20*, 9–16.
Wirz, L., Wacker, J., Felten, A., Reuter, M., & Schwabe, L. (2017). A deletion variant of the alpha2b-adrenoceptor modulates the stress-induced shift from "Cognitive" to "Habit" memory. *Journal of Neuroscience, 37*, 2149–2160.
Wolf, O. T. (2009). Stress and memory in humans: Twelve years of progress? *Brain Research, 1293*, 142–154.
Wolf, O. T. (2017). Stress and memory retrieval: Mechanisms and consequences. *Current Opinion in Behavioral Sciences, 14*, 40–46.
Wood, W., & Rünger, D. (2016). Psychology of habit. Annual Review of Psychology 67, 11.1–11.26.
Worbe, Y., Savulich, G., de Wit, S., Fernandez-Egea, E., & Robbins, T. W. (2015). Tryptophan depletion promotes habitual over goal-directed control of appetitive responding in humans. *International Journal of Neuropsychopharmacology, 18*, 1–9.