Motivational Control of Habits: A Preregistered fMRI Study

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Author Note

This manuscript and the raw data of the pilot research reported in this document can be accessed at https://osf.io/hbznq/?view_only=5414b4189b2e4880ac614ec9a27807bf. -For additional statistical analyses of the pilot study see the supplementary information file.

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Abstract

Habitual action is typically distinguished from goal-directed action by its insensitivity to changes in the reward value. There is an ongoing discussion whether this insensitivity is an intrinsic design feature of habits or, rather, a function of the cognitive system that controls habitual action tendencies. The proposed study investigates this issue using functional magnetic resonance imaging of brain activity before and after a reward devaluation in an outcome-selective Pavlovian-to-instrumental transfer (PIT) paradigm. Based on expected value of control theory, it is hypothesized that neural activity of the dorsal anterior cingulate cortex (dACC) is increased during presentations of Pavlovian cues associated with a devalued outcome~~, indexing the monitoring and implementation of control during the PIT test~~. This neural activity is hypothesized to reflect increased control allocation to situations predictive of a devalued reward.

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Keywords: outcome-selective Pavlovian-to-instrumental transfer; reward devaluation; habit; goal-directed action; expected value of control; anterior cingulate cortex function; fMRI;

A hallmark of habitual actions is that, once they are established, they become insensitive to changes in the values of associated action rewards. ~~An everyday example is continuation of snacking although having reached a state of satiety.~~ In dual action psychology, *habitual* actions are defined as behaviours that are "simply triggered by the appropriate stimulus", which are contrasted with *goal-directed* actions that are controlled "by the current value of their goals through knowledge about the instrumental actions and their consequences" (Dickinson, 1985, p. 67). This distinction is also propagated by neuroscientific models that distinguished between *model-based* (goal-directed) and *model-free* (habitual) action control modes, both are subserved by distinct but interacting neural systems (Daw et al., 2005). Model-based action control has been proposed to depend on an internal model of the world that explicitly relates alternative actions to future environmental states. This mode implicates regions of the prefrontal cortex and their connections to dorsomedial striatum (caudate nucleus in primates). By contrast, model-free control relies on the retrieval of cached action values from memory without requiring an elaborate mental model to be constructed or searched; this mode is implemented by a sensorimotor cortex–basal ganglia loop that includes the dorsolateral striatum (putamen in primates) (for reviews see Balleine & O'Doherty, 2010; Dolan & Dayan, 2013; Graybiel & Grafton, 2015; Yin & Knowlton, 2006).

Notably, the mode of behaviour control could be determined with experimental outcome revaluation procedures that change the value of associated action outcomes after training and examine the effect on behavioural performance: If performance is sensitive to manipulations of outcome value (for example, if the rate of responding decreases after outcome devaluation), then it is concluded that the behaviour was controlled by the anticipation of the outcome—and hence goal-directed. If performance is insensitive to these manipulations, then it is concluded that the behaviour was controlled by antecedent stimuli—and hence habitual. Importantly, this

test should occur in the absence of the revalued outcome to prevent new action learning during the (extinction) test.

A large number of behavioural and neuroscientific studies with rodents and humans were conducted using this revaluation assay. In an early study, Adams and Dickinson (1981) found that rats trained to press a lever for food would subsequently cease lever pressing in an extinction test after the food pellets were separately paired with a toxin (thereby devaluing the food reinforcer). They concluded that lever pressing was goal-directed. However, when the rats received more extended training with the food reinforcer, they continued to press the lever even after the devaluation treatment, demonstrating outcome insensitivity more consistent with a habitual control mode (Adams, 1982). Similar effects have been ~~demonstrated~~ reported in fMRI studies with humans, demonstrating that orbitofrontal cortex (OFC) and amygdala regions track changes in the value of predicted rewards (Gottfried et al., 2003; O'Doherty et al., 2000; Tanaka et al., 2008; Valentin et al., 2007). With overtraining, however, cue-related activity in a specific region of the posterior dorsolateral putamen increased as the instrumental training progressed, which was interpreted as a shift from goal-directed to habitual action control (Tricomi et al., 2009).

~~Valentin and colleagues (2007) used fMRI to examine brain activity during an instrumental learning phase of different food rewards. After training, one of these foods was devalued by feeding the participant to satiety on that food. The participants were then scanned again, while being re-exposed to the instrumental choice procedure in extinction. Results indicated that neural activity in the orbitofrontal cortex (OFC) was modulated during selection of the devalued compared with a non-devalued action. This finding fits with other research showing that OFC and amygdala regions track changes in the value of predicted rewards (Gottfried et al., 2003; O'Doherty et al., 2000; Tanaka et al., 2008). In another study (Tricomi~~

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et al., 2009), one group of participants received limited instrumental training for food rewards during fMRI scanning, while another group received six times as much training distributed across three consecutive days. After the training, one of the two food rewards was devalued through selective satiation (i.e., participants could eat that food ad libitum) and the two groups were scanned again during action choices in a subsequent extinction test. Behavioural results mirrored those of the animal studies: responding for the devalued food in the extinction test decreased in the group with minimal training, whereas it did not in the overtrained group. In addition, fMRI data acquired during the instrumental training phases showed increased cue-related activity in a specific region of the posterior dorsolateral putamen as training progressed, which was interpreted as a shift from goal-directed to habitual action control. fMRI data during the extinction test were however not analysed due to insufficient usable data.

To summarize, brain imaging studies on habit acquisition through overtraining found that the dorsolateral striatum is involved in habit acquisition, whereas the ventromedial prefrontal cortex is sensitive to changes in outcomes values and implicated in the control of goal-directed action. A logical problem with the overtraining procedure however is that it conflates the acquisition of habits with performance improvements that come with practice (i.e., the expression of acquired habits) (for a discussion and investigation of this point issue see Liljeholm et al., 2015). Therefore, the most stringent way for studying the implementation of habitual control is to exclude exposure to repeated S-R pairings before the test phase at all. This could be realized with an experimental paradigm that was dubbed “Pavlovian-to-instrumental transfer”—or in short: PIT.

Pavlovian-to-Instrumental Transfer

In outcome-selective PIT, reward-related cues that are predictive of particular rewards prime instrumental responses that are associated with these rewards. Figure 1 shows the basic

procedure of an animal study using the PIT paradigm. In a first *Pavlovian training phase*, the animals learn to associate stimulus cues (e.g., CS1: a high-pitched tone and CS2: a low-pitched tone) with the delivery of particular outcomes (e.g., O1: food pellets and O2: a sucrose solution). In a subsequent *instrumental training phase*, they could earn the rewards by own responding (e.g., R1: lever on the left; R2: lever on the right). In a final *transfer test phase*, the animals could continue working for the rewards but this time with intermittent presentations of the reward-related cues and without delivery of the rewards (extinction test). Many studies with rodents and humans showed that the rate of responding for a specific reward is elevated by the presentation of a cue that is associated with the same reward (e.g., CS1: R1>R2) relative to control conditions with an unpaired stimulus cue or baseline periods with no cue (see the hypothetical test result in the right panel of Figure 1) (for reviews see Cartoni et al., 2016; Holmes et al., 2010; Urcuioli, 2005). This effect was dubbed the outcome-selective PIT effect, or in short: the *specific* PIT effect.

Researchers also observed another transfer effect which was labeled *general* PIT effect. Here, the CS enhances responses directed to other rewards relative to control conditions in which no Pavlovian cue is present (Estes, 1943; Talmi et al., 2008). Furthermore, both types of effects could be investigated in a single paradigm which was named “a full transfer paradigm” (Cartoni et al., 2016).

Figure 1

Illustration of the Outcome-Selective PIT Paradigm With the Hypothetical Test Result

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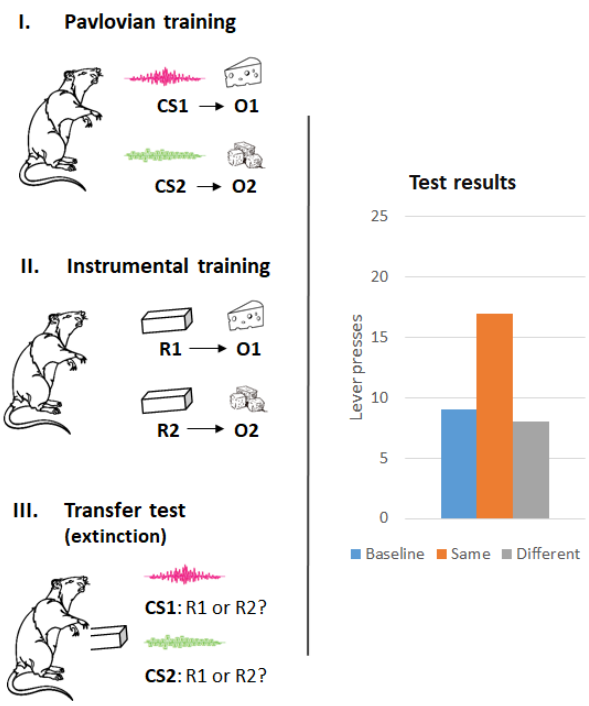

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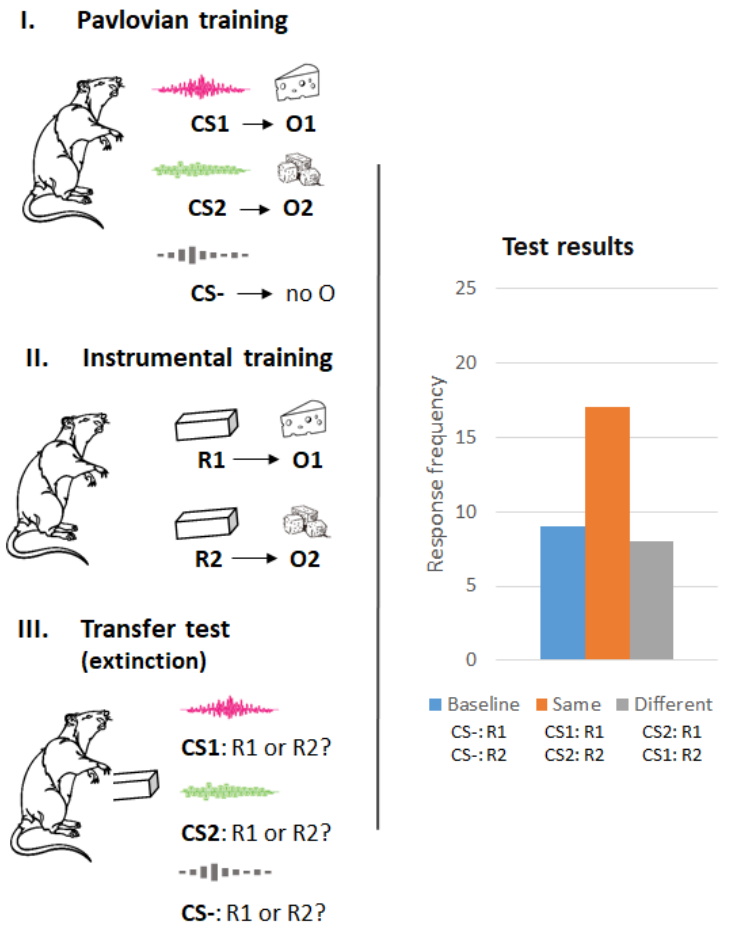

The critical feature of the PIT paradigm is that Pavlovian relations and instrumental relations are trained in separate phases, which means that transfer in the test phase occurs without prior training of the instrumental action in the presence of Pavlovian cues. This design therefore allows to study the expression of habits distinct from habit acquisition.

Researchers proposed different accounts for specific and general PIT effects. General PIT effects were typically explained with CS-triggered activations of motivational systems on

a central level that prime preparatory responses for appetition and defense (Dickinson & Balleine, 2002; Rescorla & Solomon, 1967). Specific PIT effects, in contrast, were typically explained with a cue-triggered activation of sensory representations of action outcomes that, in turn, primes the response producing that outcome (S-O-R theory; Trapold & Overmier, 1972). These theories assume that PIT effects are mediated by a chain of associative links that form during the training phases. Modern accounts of specific PIT effects in humans also highlighted the role of propositional processes and the influence of a person's explicit beliefs about the availability of outcomes and their values (Mahlberg et al., 2019). This propositional approach was also supported by studies of task instructions that could reverse the direction of specific PIT effects without prior training, but only if the person had sufficient processing resources (Seabrooke et al., 2016; Seabrooke, Wills, et al., 2019).

Neuroscientific studies with animals have shown that a distributed set of brain regions is necessary for the expression of PIT, including the amygdala (Blundell et al., 2001; Hall et al., 2001; Holland & Gallagher, 2003), nucleus accumbens (Hall et al., 2001; Corbit et al., 2001; de Borchgrave et al., 2002), ventral striatum (Cardinal et al., 2003; Corbit and Balleine, 2005), and ventral tegmental area (Corbit et al., 2007; Murschall & Hauber, 2006), suggesting the involvement of dopaminergic pathways (Lex & Hauber, 2008). Lesions studies in rats found that specific transfer was abolished by basolateral amygdala and nucleus accumbens shell lesions, whereas general transfer was abolished by lesions of the central nucleus of the amygdala and the nucleus accumbens core (Corbit & Balleine, 2005, 2011). This is corroborated by human neuroimaging studies that reported an involvement of the striatum in specific PIT (Bray et al., 2008; Lewis et al., 2013; Mendelsohn et al., 2014; van Steenbergen et al., 2017; van Timmeren et al., 2020) and of the amygdala and nucleus accumbens in general PIT (Prévost et al., 2012; Talmi et al., 2008). In neuroimaging analyses of specific transfer effects, Bray and colleagues (2008) reported a contribution of the ventrolateral putamen but not

the amygdala in specific PIT. Using high-resolution brain-imaging, Prevost and colleagues (2012) however could show that, in addition to the ventrolateral putamen, a region in the ventral amygdala within the boundaries of the basolateral (BLA) complex is involved, which accords with lesion studies on rodents (Johnson et al., 2009). The BLA is suggested to be involved in the processing of specific sensory features of an outcome (Balleine & Killcross, 2006), which in turn may affect action selection and execution via the acquired O-R link.

We know of only one published fMRI study with humans that investigated neuronal correlates of specific transfer effects following the devaluation of an action outcome (van Steenbergen et al., 2017). In ~~This~~ this study, ~~trained~~ participants were trained to associate specific keypresses and symbols with particular food rewards (popcorn, Smarties). Following the training, one of the two food rewards was devalued by feeding to satiety. Subsequently, participants could work again for the food rewards with intermittent presentations of the reward-related cues. Behavioral data showed that satiation failed to reduce cue-dependent food-seeking. Furthermore, during cued trials, the blood oxygenation level-dependent (BOLD) activity in a region of the putamen differentiated between actions that were consistent and inconsistent with the cued outcome. When choices were made in the absence of Pavlovian cues, the posterior ventromedial prefrontal cortex tracked the values of the expected food rewards. Overall, these findings accord with previous studies that suggested an involvement of the ventromedial prefrontal cortex (vmPFC) in goal-directed action (Gläscher et al., 2009; Gottfried et al., 2003; Valentin et al., 2007), and the putamen and BLA in cue-driven, habitual responding (Bray et al., 2008; Prévost et al., 2012).

Dual Action or Controlled Action?

Observations of an insensitivity to posttraining devaluation treatments were interpreted to support a dual action psychology that conceptualizes habits as associative S-R structures that

operate autonomously from reward expectations (Ceceli & Tricomi, 2018; Dayan, 2009; Dickinson, 1985). This interpretation is however challenged by an increasing number of studies that observed behavioral adjustments in various PIT tests following the devaluation of a reward (Allman et al., 2010; Eder & Dignath, 2016a, 2016b; Hinojosa-Aguayo & Gonzalez, 2019; Seabrooke et al., 2017; Seabrooke, Hogarth, et al., 2019). For example, Allman and colleagues trained human participants to associate specific symbols and actions with particular monetary outcomes. In a subsequent transfer test, participants exhibited a specific transfer effect. After this test, participants were informed that one of the currencies has lost its value due to a financial crash. Participants then worked again on a transfer test. Results showed that the cue associated with the now-devalued outcome has now lost its capacity to elevate the response rate. Eder and Dignath (2016a) reproduced this result using a similar paradigm and in another study when a food outcome (lemonade) was devalued by pairing it with bad-tasting Tween20. In this latter study, however, the elimination was observed only when participants were to drink the devalued lemonade immediately after the transfer phase but not when consumption was postponed. On the basis of these results, Eder and Dignath (2019) proposed that cue-motivated action tendencies in PIT tasks are not insensitive to outcome values by psychological design but, rather, by lacking the motivation for control. This motivation can be created (among other factors) by strong devaluation treatments that result in a complete and immediate loss of the reward (e.g., no monetary value), in comparison to standard treatments involving feeding to satiety, such as smoking cigarettes or eating chocolate, that likely leave substantial parts of the reinforcers intact (for a review see ~~(for evidence with rodents see~~ (Kruglanski & Szumowska, 2020)~~. Hence, an explanation for the motivational insensitivity in previous studies could be that the treatment was simply not strong enough to induce a motivation to control the cue-~~

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~~motivated response tendency.~~[1] It should be highlighted that weak and/or incomplete outcome devaluation is not the only explanation for spared PIT tendencies in previous studies. Other possible explanations are (i) species-specific processes differing between humans and rodents (but see Balleine & O'Doherty, 2010); (ii) systematic differences in baseline responding (Seabrooke, Hogarth, et al., 2019), (iii) residual beliefs about the informativeness of the Pavlovian cues with respect to the availability of outcomes (Seabrooke et al., 2017), (iv) and the operation of additional goals during the PIT test (De Houwer et al., 2018; Hommel, 2019). Latter explanations concur in the present argument that the motivational insensitivity observed in human PIT studies was the result of a goal-dependent process—and not a design feature of a 'habitual action controller'.

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Eder and Dignath (2019) referred to Expected Value of Control (EVC) theory for an account of the conditions in which habitual PIT tendencies become motivationally controlled. EVC theory assumes that (habitual) 'default' processes become cognitively controlled when the expected benefits of response control outweighs the intrinsic cost to engaging in control (Shenhav et al., 2013). According to this theory, a central hub for this weighting process is the

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dorsal anterior cingulate cortex (dACC) that receives inputs from brain areas responsible for the valuation of incoming stimuli or action outcomes (OFC, vmPFC, amygdala) and that sends output signals to areas responsible for the implementation of control (lateral PFC, motor cortex, striatum, subthalamic nucleus). It is assumed that the dACC monitors ongoing processing ~~for~~ of signals indicative ~~for~~ of the need for control, evaluates the demands for control, and allocates control to downstream regions (Botvinick, 2007; Shenhav et al., 2016). In PIT tasks, the default response that must be potentially overcome is the cue-instigated action tendency. Before the revaluation treatment, there exists no valuable action that could be selectively increased for a better payoff. Expected payoffs however change dramatically after a strong devaluation of the outcome. Now, there exists a clear difference in the value of action outcomes. Control is intensified when the costs of obtaining a devalued outcome justify the costs of engaging in control, resulting in a selective suppression of the associated response tendency. On the neural level, activity of dACC in a transfer test should thus increase during presentations of Pavlovian cues predictive of the devalued outcome, indexing the monitoring and implementation of control. This hypothesis is tested in the proposed fMRI study.

Pilot Study

In order to prepare the experimental design for the current fMRI study, we conducted a pilot study with a stock market paradigm adapted from Allman et al. (2010) and Eder & Dignath (2016b, Experiment 2). Participants were first trained in separate phases to associate specific company emblems and instrumental actions with particular (fictitious) African currencies. Outcome-selective transfer in a PIT test was then measured by the extent to which a company emblem increased responses associated with the same currency. Then, one of the currencies was devalued by instruction, and cue-motivated response tendencies were again assessed in a

second transfer test. This design hence allowed a comparison of specific PIT tendencies before and after the devaluation of a specific outcome.

Method

Participants

Using a similar PIT paradigm, Eder & Dignath (2016, Experiment 2; n = 45) reported large outcome-specific PIT effects with η_p^2 = .387 and η_p^2 = .193 for the first and second transfer tests, respectively. Even more important for the present research, the ANOVA interaction effect indicating different magnitudes of specific PIT effects in the transfer tests was η_p^2 = .152, and d_z = 0.53 for the comparison of specific transfer effects before and after devaluation of the response-contingent monetary reward. Based on the latter effect size estimate, an a-priori power analysis (conducted with G*Power 3.1.9.7, Faul et al., 2007) suggested that N = 24 participants would be needed to detect an analogous or larger effect with sufficient statistical power (1-β = .80) in a one-sided matched pairs t-test with α = .05. This sample size was also needed to fill each cell of the counterbalanced study design (see Design below). The study was approved by the local ethics committee (GZEK 2014-10) and all participants (N = 24; 17 females, 7 males; 20 right-handers; age M = 26.2 years, SD = 6.1) provided written consent.

Design

The experiment had a 2 (transfer test: before devaluation *vs* after devaluation) *x* 4 (Pavlovian relation: CS1/Currency 1 *vs* CS2/Currency 2 *vs* CS3/Currency 3 *vs* CS-/no currency) *x* 3 (instrumental relation: R1/Currency 1 vs R2/Currency 2 vs R3/Currency 3) repeated-measures design. R1 always worked for the (to-be) devalued currency. The following factors were counterbalanced across participants: (1) The Pavlovian assignment of the geometric figures (CS) to the outcomes using a Latin square; (2) the instrumental assignment of the money

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currencies to the response keys (keys 1, 2, and 3). This counterbalancing procedure resulted in 4 x 6 = 24 combinations.

Apparatus and Material

Participants were seated at a distance of about 60 cm from a 17"" VGA color monitor. Stimulus presentation and measurement of response latencies were controlled by a software timer with video synchronization (E-Prime 3.0 Professional; Psychology Software Tools, Inc.). Participants pressed the keys "1", "2" and "3" of the number pad of the computer keyboard with the fingers of their dominant hand.

Pavlovian cues were 4 visually distinct geometric figures (1 star, 1 square, 1 triangle, 1 circle). Outcomes in the training phases were currency symbols: 'B$' for Botsuana Dollar; 'N$' for Niger Dollar; 'T$' for Tansania Dollar; '—' for no trade outcome.

Procedure

Table 1 gives an overview of the experimental procedure that was adapted from Eder and Dignath (2016, Experiment 2). Participants read a vignette describing the participant in the role of a stockbroker. Companies in different African countries would trade with particular fictitious African currencies (B$, N$, T$). Participants' tasks for the training phases were to figure out which company trades with which African currency (Pavlovian training) and to earn as many African dollars as possible (instrumental training). Instructions also highlighted that their profit in African dollars would be exchanged into real money (Euros) after the experiment.

Table 1

Summary of Experimental Procedure

Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Exchange Rates	Pavlovian training	Instrumental training	Transfer Test 1	Pavlovian retraining	Instrumental retraining	Revaluation	Transfer Test 2

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50 N$: €1 50 B$: €1 50 T$: €1	S1→ N$ S2→ B$ S3→ T$ S4→ --	R1→ N$ R2→ B$ R3→ T$	S1: R? S2: R? S3: R? S4: R?	S1→ N$ S2→ B$ S3→ T$ S4→ --	R1→ N$ R2→ B$ R3→ T$	20 N$: €0 20 B$: €1 20 T$: €1	S1: R? S2: R? S3: R? S4: R?

Note. Pavlovian stimuli (S) were four sets of visually distinct geometrical shapes; responses ~~(R)~~I were presses of the keys "1". "2" and "3" of the number pad; outcomes were symbols indicating earnings in different African dollar currencies (B$, N$, T$) or no earning (--). Exchange rates in Euros were displayed at the start of the experiment (Stage 1) and during the revaluation phase (Stage 7). The assignment of the outcomes to the geometric figure sets and to the responses was counterbalanced across participants (see *Design* for details)

Stage 1: Exchange Rates and Currency Rating.

Exchange rates of the African currencies were displayed on the screen, with 50 Dollars of an African currency being worth 1 Euro. Participants were then asked to evaluate each currency on a scale ranging from 0 (very bad) to 9 (very good).

Stage 2: Pavlovian Training.

Participants were informed that geometric figures will appear on the screen that represent companies. The logo of one company was represented by a circle, a second company by a triangle, a third company by a square, and a fourth logo by a star. Instructions given for this phase were the following (translated into English language):

In this part of the experiment, you will see various geometric symbols. Each symbol represents a company (company logo). One company has a CIRCLE as logo, another company a TRIANGLE, the third a SQUARE and the fourth a STAR. Since the companies only trade in a single country, each company trades with exactly one currency.

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FIND OUT WHICH COMPANY (Circle, Star, etc.) TRADES WITH WHICH SPECIFIC CURRENCY (B$, N$, etc.)!

Participants then observed 10 pairings of a company symbol with a trade outcome, distributed across ten blocks with random presentations of each figure-currency pair in a block. The company symbol was presented for 1,000 ms; after an additional 50 ms, a currency symbol (e.g., 1B$) was presented as outcome for 2,000 ms. Participants were asked to press the spacebar during the presentation of a currency symbol to confirm the trade, and to refrain from a key press if the outcome was no trade (symbol: --). This task procedure was implemented to direct the participants' attention to the outcomes (following the procedure of Allman et al., 2010). An error message appeared for 5,000 ms if the spacebar was not pressed within 2,000 ms following the presentation of the outcome or if the key was pressed in a trial with no trade outcome. The intertrial interval (ITI) ranged between 500 and 1,500 ms.

After the training, participants were asked to indicate the contingencies between the companies and the currencies. In each trial, a company symbol (circle, star, etc.) was presented and the four outcomes (3 currencies and no outcome) appeared on the screen below the company symbol. Participants were to indicate the paired outcome by pressing designated keys on the computer keyboard. Each company symbol was presented once and in randomized order. A message after each keypress indicated whether the participant's assignment was correct or incorrect. If one or more assignments were incorrect, the Pavlovian training was repeated with a reduced number of training trials ($4 \; x \; 5$ trials). After retraining, the participant answered an additional Pavlovian contingency test and the retraining continued until all answers were correct.

Stage 3: Instrumental Training.

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Instructions for this phase stated that participants could now earn African dollars with presses of response keys. Participants were informed that they could switch between keys as often as they wished and that the computer may tell them to stop pressing one particular key. In this case, they should use the other keys to earn dollars in other currencies.

A black fixation cross was presented on a white background while participants responded on three concurrent fixed ratio nine schedules (FR 9). Response keys were the keys "1", "2"and "3" of the number pad that were highlighted with LEDs of the mechanical keyboard. One response key worked for Botsuana dollars (B$), one for Niger dollars (N$), and the third for Tansania dollars (T$). Participants could switch responding between keys, and if they did so before the FR9 criterion for a key had been reached they could complete the requirement for that key when they returned to it. Once a key had been pressed nine times, a dollar sign in an African currency (+1B$; +1N$; +1T$) was presented for 2,000 ms and participants were to press the spacebar during this time to "bank" the dollar to their account. If the spacebar was not pressed, an error message appeared and the dollar was not added to the participant's account. The computer program prompted the participant to stop responding on a particular key after earnings of 20 dollars in a currency (i.e., 180 presses of the response key).

After the instrumental training, participants were asked to indicate the instrumental contingency with a press of the response key that produced the African dollar presented on the screen. African currencies were presented in randomized order. If the assignment was incorrect, the instrumental training was repeated with half the number of outcome presentations (i.e., earning of 10 dollars of each currency = 90 presses of each key).

Stages 4: Transfer Test 1.

Instructions for the transfer test stated that they could continue earning African dollars with key presses but that profits in African dollars would not be displayed in this phase. The time window for response registration was indicated by the color of a dollar sign that appeared at the center of the screen. Instructions stated that the stock market is open when the dollar sign is green and closed when red. Keypresses would only be registered during the opening times. In addition, the following information on presentations of company symbols was presented:

From time to time, a company will also trade on the stock market (i.e., a company logo will appear on the screen). These company trades do not influence your own profits.

NOTE: Your profit in African dollars is not shown in this phase. A press of the space bar is therefore not necessary.

The dollar sign was green for 12,000 ms and red for an additional 4,000-12,000 ms (with a positively skewed distribution: 4-8s in 75% and 9-12s in 25% of the trials). Two seconds after onset of the green dollar sign, a company symbol (geometric figure) superimposed on the green dollar sign was shown for 8,000 ms. Each of the four company symbols presented during the Pavlovian phase were shown in randomized order in a block. The transfer test had 12 blocks (48 trials). With registration of the ninth press of a response key, one dollar was added to the tally of that African currency; however, profits in African dollars were not presented as outcomes during this stage, corresponding formally with an extinction test.

Stages 5 to 8: Pavlovian and Instrumental Retraining, Outcome Devaluation, and Transfer Test 2.

Before devaluation, the Pavlovian training (Stage 4) and the instrumental training (Stage 5) were repeated with half the number of trials in each stage. This re-training served to

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reestablish the Pavlovian and instrumental contingencies after the extinction test (Transfer Test 1). Following retraining, and immediately prior to the revaluation treatment, the African dollars earned so far were exchanged for Euros, and the tally for each African currency was reset to zero. Then, two of the African currencies were revalued with the following instructions written in red:

-- ALERT! -- ALERT! -- ALERT! --

NEW EXCHANGE RATES!

The exchange rates of African dollars to Euros have changed due to an international financial crisis.

Exchange rates are now:

20 N$ = €0
20 T$ = €1
20 B$ = €1

The devaluation of an African currency was counterbalanced across participants. Participants worked through a second transfer test (Stage 7) that was identical with the first transfer test. Participants then rated again the African currencies as a manipulation check of the revaluation treatment (see Stage 1 for the rating procedure).

Finally, participants were paid and debriefed with respect to the nature of the study.

Data Analyses

Mean frequencies of key presses during the presentation of the CS (8 s) in Transfer Test 1 were analyzed with a 4 *x* 3 rm-ANOVA with the factors *Pavlovian cue* (CS1, CS2, CS3, CS-) and *Response* (R1, R2, R3). It was hypothesized that response rates would be elevated by presentations of Pavlovian cues with common outcomes (i.e., a statistical interaction effect between Pavlovian Cue and Response). Outcome-selective PIT was assessed with a comparison of the response rate in the presence of Pavlovian cues associated with the same outcome relative to the response rate in the baseline condition with CS-. For follow-up comparisons, response rates in the presence of matching Pavlovian cues were consequently directly compared with

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those in the presence of neutral cues (i.e., CS1:R1 *vs* CS-:R1, CS2:R2 *vs* CS-:R2, CS3:R3 *vs* CS-:R3) using paired-samples t-tests. For the second transfer test, response rates were analogously analyzed, whereby O1 designates the devalued currency.

Magnitudes of PIT effects in the two transfer tests were also directly compared to examine whether they were changed by the revaluation treatment. For this comparison, we first transformed the raw values into z scores to adjust for differences in the base rates of key presses after the devaluation treatment (Bush et al., 1993). The a priori significance level was set to $\alpha = .05$ for all analyses and *p*-values were corrected for violations of sphericity using Greenhouse-Geisser. Standardized effect sizes (Cohen's *d*, partial eta-square) are reported where appropriate.

The raw data underlying the findings reported below can be accessed at https://osf.io/hbznq/?view_only=5414b4189b2e4880ac614ec9a27807bf (view-only link).

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Results

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For the sake of brevity, only the main comparison of specific PIT effects before and after devaluation is reported below. The full report with analyses of performance in each transfer test and currency ratings can be found in a supplementary information file.

~~Outcome Ratings~~

~~In a first step, we examined the effectiveness of the devaluation procedure on explicit ratings of monetary outcomes (African currencies, see Table 2) by calculating a 3 x 2 rm-ANOVA with the factors *Currency* (1-3) and *Time Period* (before vs. after devaluation). The main effect of *Time Period* was not significant ($F<1$), but the main effect of currency, $F(1.09, 46) = 92.24$, $p < .001$, $\eta_p^2 = .800$, and the interaction term were, $F(1.16, 52) = 85.37$, $p < .001$, $\eta_p^2 = .788$. As expected, ratings did not differ before devaluation and decreased for the devalued outcome after the devaluation treatment.~~

Table 2

Ratings of Monetary Outcomes (M, SD) Before and After the Devaluation of O1

Outcome	Before	After
O1	4.79 (2.6)	1.00 (1.4)
O2	4.71 (2.4)	6.38 (2.4)
O3	4.75 (2. 5)	6.17 (2.5)

Note. Ratings on a scale from 0 (very bad) to 9 (very good).

Transfer Test 1 (Before Devaluation)

In the 4 *x* 3 rm-ANOVA of response rates, the main effect of *Pavlovian cue*, $F(1.05, 69) = 4.82$, $p = .004$, $\eta_p^2 = .173$, the main effect of *Response*, $F(2, 46) = 12.07$, $p < .001$, $\eta_p^2 = .344$, and most importantly, the interaction effect were significant, $F(2.97, 138) = 7.18$, $p < .001$, $\eta_p^2 = .238$. As shown in Fig. 2 (Transfer Test 1), Pavlovian cues selectively enhanced the frequency of the response that worked for the same outcome relative to the CS , with $t(23) = 2.69$, $p = .007$, $d_z = 0.55$ for O1, $t(23) = 2.75$, $p = .006$, $d_z = 0.56$ for O2, and $t(23) = 5.04$, $p < .001$, $d_z = 1.03$ for O3.

Transfer Test 2 (After Devaluation)

In this transfer test, O1 designates the devalued currency. In the 4 *x* 3 rm-ANOVA, the main effect of *Response* was significant, $F(2, 46) = 65.50$, $p < .001$, $\eta_p^2 = .740$. Response rates were substantially reduced for the devalued currency ($M = 3.6$) and on high levels for the other two currencies, with $Ms = 26.1$ and 21.9, respectively. Thus, the devaluation treatment was effective. The main effect of *Pavlovian cue*, $F(1.17, 26.88) = 5.19$, $p = .026$, $\eta_p^2 = .184$, and the interaction effect between both factors were also significant, $F(1.87, 42.95) = 13.23$, $p < .001$, $\eta_p^2 = .365$, indexing an outcome selective PIT effect (see Transfer Test 2 in Fig. 2). Planned comparisons with neutral cues revealed significant elevations of the keypress rates for the

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~~valued outcomes O2 and O3, $t(23) = 4.31$, $p < .001$, $d_z = 0.88$, and $t(23) = 4.60$, $p < .001$, $d_z = 0.94$; in contrast, working for the devalued currency (R1) was not significantly increased by the presentation of a matching cue (S1) relative to the neutral cue condition (Sn), $t(23) = 1.55$, $p = .135$, $d_z = 0.317$.~~

Comparison of Specific PIT Effects Before and After Devaluation

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Specific PIT effects were computed for each outcome by subtracting the z-transformed response rate in the baseline condition with CS- presentations from the response rate in the condition with presentations of matching CS+. This computation was done for each transfer test. Resulting values (see Fig. 2) were then entered in a repeated-measures ANOVA with *specific PIT effect* (O1, O2, O3) and *Transfer Test* (1, 2), whereby O1 designated the (later) devalued currency.

Results showed a significant main effect of *specific PIT effect*, $F(2, 46) = 10.77$, $p < .001$, $\eta_p^2 = .319$, and a significant interaction effect between both factors, $F(2, 46) = 4.29$, $p = .020$, $\eta_p^2 = .157$. The main effect of *Transfer Test* was not significant, $F(1, 23) = 1.49$, $p = .235$, $\eta_p^2 = .061$. Follow-up comparisons between Transfer Test phases using *t*-tests confirmed a significant reduction of the cue-motivated action tendency after devaluation of the outcome (O1), $t(23) = 2.69$, $p = .013$, $d_z = 0.55$. The PIT effect in Transfer Test 2 did also not differ significantly from zero in a one-sample *t*-test, $t(23) = 0.60$, $p = .552$. In contrast, magnitudes of PIT effects for the valued currencies in both transfer tests were not significantly different, with $t(23) = -0.55$, $p = .585$ for O2, and $t(23) = 0.32$, $p = .753$ for O3.

Figure 2

Z-Transformed PIT Effects for Each Outcome Before and After Devaluation of Outcome 1

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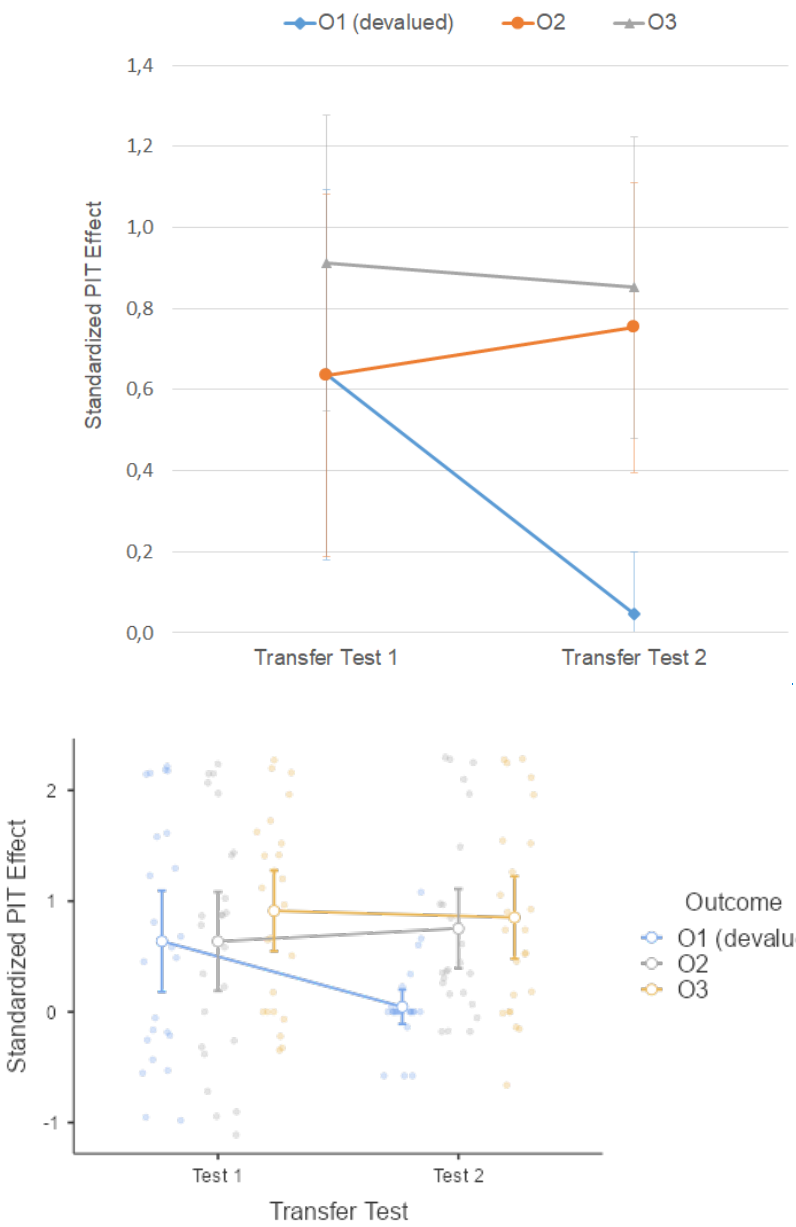

Note. Error bars show the 0.95 confidence interval. Dots show individual data points.

Planned Functional MRI Study

The design and procedure of the pilot study is used for the fMRI study. Table ~~3~~ 2 provides an overview of the research hypotheses and the study plan.

Statistical Hypotheses and Sample Size Calculation

Sample size calculation is based on a-priori power analyses for statistical hypotheses that are central for the investigation of the research question. Standardized effect sizes of behavioral effects obtained in the pilot study are used as effect size estimates for the power analyses. For this power analysis approach, we assume a ~~logical~~close relationship ~~relation~~ between magnitudes of behavioral effects and magnitudes of fMRI activity in ~~hypothesized subserving~~ brain regions hypothesized to mediate the behavioral effects (Eder & Dignath, 2019). There are four statistical effects that are of particular theoretical relevance for the present research question. In the following, we will describe each statistical hypothesis and the corresponding a priori power analysis conducted with G*Power 3.1.9.7 (Faul et al., 2007).

Statistical Hypothesis 1: Effect of devaluation treatment

If the devaluation treatment was effective, the rate of working for the now-devalued outcome (R1) should be significantly lower in Transfer Test 2 (after devaluation) relative to Transfer Test 1 (before devaluation). In statistical terms, this means that numbers of keypresses (R1) during presentations of the neutral cue (CS-) is lower in Transfer Test 2 than in Transfer Test 1. This is indicated by a significant effect of CS- on R1 responding in a univariate ANOVA, which is identical ~~with~~to a paired t-test for R1 responding in Transfer Test 1 and 2. A corresponding one-tailed t-test of the pilot study data revealed a large effect with dz = 1.10, 95% CI [0.59, 1.61]. The a prior power analysis indicates that a minimum sample size of n = 11 participants would be needed to detect this effect with high statistical power (1-β = 0.95) in a corresponding test.

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Statistical Hypothesis 2: Outcome-specific PIT effect before devaluation (PIT Test 1)

Pavlovian cues (CS1, CS2, CS3) should specifically increase the rate of keypresses associated with the same outcome (R1, R2, R3, respectively) relative to the baseline condition (with presentations of CS-). Statistically, this is expressed in a significant 2-way interaction effect between Pavlovian Cue (CS1, CS2, CS3, CS-) and Instrumental Relation (R1, R2, R3). Effect size of the corresponding ANOVA effect in the pilot study was $\eta_p^2 = .238$. With this effect size estimate, the a priori analysis demonstrates that a minimum of n = 10 subjects would needed to detect this effect (and larger) with high statistical power (1-β = 0.95) in a corresponding statistical test.

Statistical Hypothesis 3: Outcome-specific PIT effect after devaluation (PIT Test 2)

After devaluation of the outcome associated with CS1 and R1, the remaining Pavlovian cues (CS2, CS3) should still increase keypresses that were associated with a matching outcome (R2, R3, respectively) relative to the baseline condition (CS-). Thus, a 3 x 2 ANOVA on the response rates in Transfer Test 2 is performed. Effect size of the hypothesized ANOVA interaction effect in the pilot study was $\eta_p^2 = .430$. The a priori analysis revealed that a minimum of n = 8 would be needed to detect this effect or larger with high statistical power in a corresponding statistical test.

Statistical Hypothesis 4: Reduced PIT effect after relative to before devaluation of the associated outcome

Statistically, this hypothesis corresponds with a 3-way interaction effect between Pavlovian Cue, Instrumental Relation, and Transfer Test in the omnibus ANOVA, and for a more specific follow-up test of the hypothesized pattern, a comparison of (z-transformed) PIT effects before and after devaluation of the associated outcome (for details on the computation of the PIT effect see the section *Comparison of Specific PIT Effects Before and After*

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Devaluation above). The pilot study showed a reduction of the specific PIT effect in the magnitude of d_z = 0.55. ~~This effect size was used for sample size calculation with G*Power 3.1.9.7.~~ The a-priori power analysis showed that N = 38 participants ~~will~~ would be needed to detect an effect of this magnitude ~~and~~ or larger with ~~sufficient~~ high statistical power (1-beta = 0.95) in a ~~one-tailed matched-paired t-test with α = .05~~corresponding test.

In line with the results of the a priori analyses described above, we aim to collect data of n = 38 participants. This means, potential dropouts will be replaced until reaching a ~~valid~~final sample size of n = 38 valid datasets~~was reached~~.

Data Exclusion on the Participant Level

We plan to replace ~~any~~ participant~~s~~ who drop~~s~~ out due to ~~a~~ technical failure~~reason or for another reason~~and/or large head movements during MRI measurement (> 2mm translation or >2° rotation within one of the Transfer Test phases)~~a high number of movement artefacts~~. In addition, participation ~~will be~~is terminated when the participant is unable to indicate the correct Pavlovian relation after one testing hour ~~after one testing hour~~ and/or the instrumental relations after relearning.

MRI Data Acquisition and Preprocessing

Data will be acquired on a Siemens Skyra 3T scanner using a 32-channel head coil. Functional data will be obtained using a T2*-sensitive gradient echo-planar imaging (EPI) multiband sequence with 42 slices (voxel size 2 × 2 × 2 mm^3, 1 mm gap between slices) oriented along the anterior commissure–posterior commissure axis (repetition time [TR] = 1,340 ms; echo time [TE] = 25 ms; flip angle = 60°; FOV = 216 × 216 mm; GRAPPA with PAT-factor 2; multiband acceleration factor: 2). Additionally, isotropic high-resolution (1 × 1 × 1 mm^3) structural images will be recorded using a T1-weighted coronal-oriented MPRAGE sequence with 240 slices.

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Image processing and statistical analyses will be carried out using Statistical Parametric Mapping (SPM12; Wellcome Department of Imaging Neuroscience, London, UK). Unless otherwise noted, SPM12 default values will be used for the respective preprocessing steps. We will discard the first four volumes of each time series to account for T1 equilibration effects. Volumes will then be slice time corrected, realigned and unwarped using the mean EPI image. Subsequently the structural T1 image will be coregistered to the mean EPI image and T1 images will be segmented using the DARTEL procedure to create structural templates across subjects as well as individual flow fields. These flow fields will then be used to spatially normalize the EPI images as well as the structural T1 images into MNI space. For the EPI images, data will be stored with a voxel size of 2 × 2 × 2 mm^3 and smoothed using a 6 mm full-width at half maximum (FWHM) isotropic Gaussian kernel. Structural T1 images will be stored with a voxel size of 1 × 1 × 1 mm^3 and averaged across participants. The resulting mean image will be used to illustrate the results of the functional analyses (e.g., as overlay of statistical parametric maps).

Specification of fMRI Models for a Test of Brain Activity Hypotheses

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Statistical analyses of neural activations in the Transfer Test 1 and 2 phases will be accomplished using the two-level random effects GLM approach as implemented in SPM12. At the single subject level, we are going to model the 8,000 ms response phases (i.e., when the dollar sign is green and a company symbol shown) as separate boxcar functions for each *Pavlovian cue* (CS1, CS2, CS3, CS-). Additional regressors of no interest will include boxcar functions for the initial 2,000 ms response phase without any *Pavlovian cue* and the 2,000 ms response phase after the offset of the *Pavlovian cue*, respectively. Individual behavioral responses will be modeled as stick functions for each button press, separately for the different *Responses* (R1, R2, R3). All regressors will be convolved with the canonical hemodynamic response function as implemented in SPM12. Before estimating the model, EPI images will be

high-pass filtered at 128 s, and an autoregressive AR(1) model will be used to account for serial correlations in fMRI time series.

Statistical analyses on the group level involve one-sample t-tests on activation difference maps of each Pavlovian cue minus the neutral cue (i.e., CS1 *vs* CS-, CS2 *vs* CS-, CS3 *vs* CS-) separately for each Transfer Test phase. Moreover, to directly compare patterns of brain activation before and after devaluation, we will first assess general differences between Transfer Test phases by calculating a paired t-test between average activation differences of all Pavlovian cues minus the neutral cue (i.e., (CS1 + CS2 + CS3)/3 *vs* CS-) in the second as compared to the first Transfer Test phase. Afterwards, we will specifically focus on differences between devaluated and non-devaluated cues by calculating separate paired t-tests between activation difference maps of each Pavlovian cue minus the neutral cue (i.e., CS1 *vs* CS-, CS2 *vs* CS-, CS3 *vs* CS-) in the second as compared to the first Transfer Test phase.

We expect a general increase of activity in the dACC from the first to the second Transfer Test phase indexing response monitoring and implementation of cognitive control. Moreover, dACC activity should particularly increase during presentations of the Pavlovian cue predictive of the devalued outcome in Transfer Test 2 as compared to Transfer Test 1. Reduced differences between the two Transfer Test phases are expected for the other two Pavlovian cues.

Since analyses primarily focus on the dACC, we will use a small volume correction for this region of interest (ROI). Following previous suggestions (Spunt et al., 2012), the respective ROI will be generated by extracting a binary mask including the bilateral anterior and middle cingulate and paracingulate gyri from the automated anatomical labeling atlas (Rolls et al., 2015) and trimming this mask in the anterior-posterior ($36 \geq y \geq 0$) as well as the ventral-dorsal plane ($z > 4$). The size of this ROI amounts to 18,912 mm^3. Furthermore, to consider other brain regions implicated in the control and monitoring of response tendencies, we will also use a binarized mask based on a Neurosynth meta-analysis of 598 human neuroimaging studies

associated with cognitive control (retrieved on September 29, 2021 from http://neurosynth.org/analyses/terms/cognitive%20control/) in a supplemental analysis. In addition to the dACC, this mask includes regions in the dorsolateral and ventrolateral prefrontal cortex, the posterior cingulate cortex as well as regions in the parietal lobe. Its size amounts to 11,360 mm^3.

Feldfunktion geändert

On the explorative level, we will also test for general differences in activation as well as for specific differences between the devalued vs. the other two Pavlovian cues between the two Transfer Test phases in brain regions that are responsible for the valuation of incoming stimuli or action outcomes (vmPFC) and areas responsible for the implementation of behavior control (amygdala, putamen). With respect to the vmPFC, we will use a bilateral mask of area 14m as described in Mackey and Petrides (2014). We will use the symmetric population maps binarized using a threshold of 4 (i.e., the resulting ROI mask contains all voxels where the probability exceeds 50% that the respective region is associated with this area). The size of this ROI amounts to 4,452 mm^3. Bilateral masks for amygdala (3744 mm^3) and putamen (16,466 mm^3) will be extracted from the automated anatomical labelling atlas 3 (Rolls et al., 2020). Finally, we will also report effects in brain regions that are not part of the respective masks when they reach statistical significance on a whole-brain threshold of $p_{FWE} < .05$.

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Table ~~3~~2

Summary of the Research Plan

Question	Hypothesis	Sampling plan	Analysis Plan	Rationale for deciding the sensitivity of the test for confirming or disconfirming the hypothesis	Interpretation given different outcomes	Theory that could be shown wrong by the outcomes
Is the insensitivity of cue-motivated action tendencies to posttraining changes in reward values an intrinsic design feature of habits (as proposed by dual-action psychologies) OR is it because the benefits of controlling "habitual" action tendencies do not outweigh the intrinsic costs of engaging in control (as suggested by expected value of control theory, EVC)?	According to EVC, cognitive control is intensified when the benefits of suppressing a dominant action tendency will justify the intrinsic costs of engaging in control. A central hub for these calculations on the neural level is the dorsal anterior cingulate cortex (dACC). In a Pavlovian-to-instrumental (PIT) transfer test, dACC activity should increase during presentations of Pavlovian cues associated with devalued outcomes relative to cues associated with non-devalued/neutral outcomes and in comparisons with PIT tests performed before the devaluation.	N = 38. A-priori power analysis for the detection of an increased dACC activation after relative to before the outcome devaluation in a one-tailed ~~matched~~ paired t-test with 1-beta = 0.95 and alpha = .05.	GLM approach with Pavlovian Cue and Responses as regressors for ~~of~~ neural activations in PIT tests before and after the devaluation treatment; follow-up analyses with t-test comparisons of activation differences before and after devaluation of the associated outcome (for details see Specification of fMRI Models for a Test of Brain Activity Hypotheses)	Effect size estimate (dz = 0.55) obtained from a behavioural pilot study (mean difference in the magnitudes of behavioural PIT effects before and after outcome devaluation).	Increased dACC activity after outcome devaluation would be in line with the EVC model of dACC function in habit control. Finding no dACC effect, and/or observing activation differences in unrelated brain regions, would not support this model.	Increased dACC activity after devaluation of the outcome would support EVC theory and challenge dual action psychologies that claim a structural independence of habits from outcome representations.

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Was the devaluation treatment effective?	Working (response rate) for the devalued outcome O1 should be lower in Transfer Test 2 after compared to before devaluation in Transfer Test 1	N = 11. A-priori power analysis for a paired t-test with 1-beta = 0.95 and alpha = .05.	One-tailed paired t-test of the response rates (R1) in the first and second transfer tests	Effect size estimate obtained from a behavioural pilot study (dz = 1.10).	Significant difference in the hypothesized would confirm that the devaluation treatment was effective.	Manipulation check (Behavioural data)
Was the procedure appropriate for generating cue-dependent ('habitual') action tendencies (Transfer Test 1)?	Pavlovian cues (CS1, CS2, CS3) should specifically increase numbers of keypresses that were associated with the same outcome (R1, R2, R3) relative to the baseline condition (with presentations of CS-).	N = 10. A-priori power analysis for a rm-ANOVA with 1-beta = 0.95 and alpha = .05.	2-way interaction effect between Pavlovian Cue (CS1, CS2, CS3, CS-) and Instrumental Relation (R1, R2, R3) in a 4x3 rm-ANOVA	Effect size estimate obtained from a behavioural pilot study (η_p^2 = 0.238).	Significant interaction effect with the hypothesized pattern would confirm that the PIT paradigm was effective in implementing cue-dependent response tendencies	Manipulation check (Behavioural data)
Was the procedure appropriate for generating cue-dependent ('habitual') action tendencies (Transfer Test 2)?	Non-devalued Pavlovian cues (CS2, CS3) should specifically increase numbers of keypresses associated with the same outcome (R2, R3) relative to the baseline condition (with presentations of CS-).	N = 8. A-priori power analysis for a rm-ANOVA with 1-beta = 0.95 and alpha = .05.	2-way interaction effect between Pavlovian Cue (CS2, CS3, CS-) and Instrumental Relation (R2, R3) in a 3x2 rm-ANOVA	Effect size estimate obtained from a behavioural pilot study (η_p^2 = 0.430).	Significant interaction effect with the hypothesized pattern would confirm that the PIT paradigm was still effective in implementing cue-dependent response tendencies in the second transfer test	Manipulation check (Behavioural data)