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Effort-based decision making and motivational deficits in stroke patients

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ABSTRACT

Motivational deficits in patients recovering from stroke are common and can reduce active participation in rehabilitation and thereby impede functional recovery. We investigated whether stroke patients with clinically reduced drive, initiation, and endurance during functional rehabilitative training (n = 30) display systematic alterations in effort-based decision making compared to age, sex, and severity-matched stroke patients (n = 30) whose drive appeared unaffected. Notably, the two groups did not differ in self-reported ratings of apathy and depression. However, on an effort-based decision-making task, stroke patients with clinically apparent drive impairment showed intact willingness to accept effort for reward, but were more likely to fail to execute the required effort compared to patients without apparent drive impairments. In other words, the decision behavioural assessment revealed that stroke patients that displayed reduced drive, initiation, and endurance during inpatient neurorehabilitation failed to persist in goal-directed effort production, even over very short periods. These findings indicate that reduced drive during rehabilitative therapy in post-stroke patients is not due to a diminished motivation to invest physical effort, but instead is related to a reduced persistence with effortful behaviour.

1. Introduction

Stroke remains a leading cause of death and long-term disability worldwide (Feigin et al., 2022). Recovery of lost physical functions, cognitive abilities, and quality of life after a stroke can be achieved through neurorehabilitative training (Platz, 2019). Such neurorehabilitative therapy is characterized by effortful training of physical and cognitive abilities and requires active, effortful participation and a high level of motivation and perseverance (Studer & Knecht, 2016; Studer et al., 2021; Yoshida et al., 2021). Rehabilitation specialists apply multiple motivational strategies to encourage their patients to perform rehabilitative training actively and persistently (Danzl et al., 2012; Oyake et al., 2020a, 2020b). Yet, despite therapists' best efforts, reductions in motivation, drive, and persistence are well documented in stroke patients (Nicholson et al., 2013; West & Bernhardt, 2012). Potential reasons for some stroke patients failing to fully and enduringly engage in rehabilitative training have been discussed in the extant literature. These reasons include social and environmental factors (Maclean & Pound, 2000), patients' beliefs and attitudes (Morris et al., 2017), dissatisfaction due to boredom or feelings of disempowerment (Luker et al., 2015), as well as neuropsychiatric conditions such as depression and apathy (Gaete & Bogousslavsky, 2008; Mayo et al., 2009).

Since functional recovery after stroke is dose-dependent on the amount of neurorehabilitative training performed (Knecht et al., 2016; Kwakkel et al., 2004; Van Peppen et al., 2004), any reduction in therapy engagement and persistence is likely to reduce patients' outcomes. Yet, quantitative research on the motivational impairments after stroke

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remains sparse, and to the best of our knowledge, no objective measures that allow characterising individual patients' motivational impairments observed during clinical practice have been developed to date.

In the current study, we tested whether stroke patients that demonstrated low drive and persistence during post-acute inpatient neurorehabilitation, as identified by their treating rehabilitation specialists, showed systematic shifts in effort-based decision making assessed with an objective behavioural probe. Effort-based decision making is characterised by a trade-off between a rewarding outcome and the required physical and/or mental effort to obtain this reward (e.g., Chong et al., 2016), and is supported by mesolimbic and nigrostriatal dopamine pathways and medial frontal brain areas, including ventromedial prefrontal cortex and anterior cingulate cortex (see e.g., reviews by Bailey et al., 2016; Le Heron et al., 2019; Lopez-Gamundi et al., 2021; Salamone et al., 2018; Walton & Bouret, 2019).

Since neurorehabilitation requires engaging in effortful training for the prospect of a long-term reward (successful recovery), we reasoned that effort-based decision-making paradigms are well suited for identifying and characterising potential systematic and generalised motivational impairments after stroke that can manifest in reduced drive and endurance during neurorehabilitation. Indeed, previous research in other neurological (Le Heron et al., 2018a; Muhammed et al., 2016) and psychiatric conditions (Saleh et al., 2021a; Treadway et al., 2012) affecting dopaminergic and prefrontal networks have linked diminished motivation and goal-directed behaviour to systematic alterations in effort-based decision making. In stroke patients, some neuropsychological investigations were able to link (the risk of) apathy and depression to basal ganglia and frontal lesions (Carnes-Vendrell et al., 2019; Douven et al., 2017; Hama et al., 2011; Nickel & Thomalla, 2017 but see also Aubignat et al., 2023; Douven et al., 2020), broadly consistent with the idea that diminished motivation in stroke patients might be linked to neuropathological changes in networks supporting effort-based decision making.

We compared, for the first time, stroke patients with and without observed motivational impairments during neurorehabilitative training (matched in age, gender, and stroke severity) on a previously validated effort-based decision-making paradigm (Chong et al., 2016). In this task, patients were repeatedly presented with a monetary offer and a physical effort required to obtain it. Effort and reward magnitudes were parametrically varied from trial to trial, and on each trial, patients decided whether to accept or reject the offer. If they chose to accept a given offer, they next had to perform the physical effort indicated to obtain the reward. The design of the task allows to assess individuals' general willingness to exert physical efforts for rewards, as well as to dissect how much their motivation is affected by effort requirements ("effort sensitivity") versus by the magnitude of rewards ("reward sensitivity") (see also Bonnelle et al., 2015). We hypothesised that stroke patients with diminished drive during rehabilitative training would display a lower effort willingness than control patients, indicating that the motivational problems observed during rehabilitative training in some stroke patients are a manifestation of a situation-unspecific disbalance in the valuation trade-off between effort and reward. We also aimed to identify whether this expected reduced willingness to exert effort for reward in the patients displaying reduced drive and endurance during rehabilitative training was linked to an increased effort sensitivity or decreased reward sensitivity, in order to inform further development of therapeutic strategies during post-stroke rehabilitation.

The patients assessed in the current study were identified by their rehabilitation specialists as showing diminished drive, initiative, and perseverance during rehabilitative training, despite having the physical capacity and abilities to perform at higher levels. They required constant external motivational prompting to initiate and sustain with therapist-guided functional exercises and nurse-assisted self-care activities. These behavioural observations align with the manifestation of reduced goal-directed behaviour in the neuropsychiatric syndrome of apathy (Marin, 1990). Apathy, characterised by diminished goal-directed behaviour, emotion, and cognition (Robert et al., 2009), is prevalent in a third of stroke survivors (van Dalen et al., 2013) and impedes physical and cognitive recovery post stroke (Mikami et al., 2013). Two recent effort-based decision-making studies in Parkinson's disease and cerebral small vessel disease found that patients with apathy demonstrated a reduced willingness to exert effort for rewards, driven by a reduced reward sensitivity (Le Heron et al., 2018a, 2018b). We therefore also administered an apathy self-report questionnaire to our stroke patients and tested whether the differences in effort-based decision making observed between our two clinical groups were explained by apathy. Finally, as depression has also been found to affect effort-based decision-making behaviour (Hartmann et al., 2013; Treadway et al., 2012), and post-stroke depression has been linked to lesions in the neural networks supporting effort-based decision making, specifically basal ganglia and frontal cortex (Douven et al., 2017), we additionally assessed patients' depression status through questionnaire measures.

2. Material and methods

2.1. Patients

The study was conducted at the Mauritius Neurorehabilitation Hospital in Meerbusch, Germany. Two groups of adult German-speaking stroke patients in the sub-acute stage of recovery took part in this study during inpatient neurorehabilitation: 1) patients who showed reduced (or no) drive, initiation, and endurance during rehabilitative training according to their treating rehabilitation specialists (n = 30, 13 women) and 2) patients who did not display any apparent motivational impairments during rehabilitative treatment. Throughout the methods and results section, we refer to group 1 as "drive-impaired stroke patients" (*DI* group) and group 2 as "not drive-impaired stroke patients" (*control* group). Drive is a distinct feature of goal-directed behaviour that refers to both energization and persistence towards a goal over time (Hebb, 1955; Kringelbach & Berridge, 2016; Wise, 1987). These two dimensions appeared to be lacking during rehabilitative treatment in the stroke patients within our target group.

Patients' drive during rehabilitative treatment was repeatedly rated by treating physical and occupational therapists and nurses during standard clinical practice using Likert scales, and were cross-validated through weekly interdisciplinary team discussions. We verified the clinical validity of these observations and ratings through a retrospective analysis of prospectively collected longitudinal data from an independent sample of 586 stroke patients which revealed that therapists' drive ratings in the first week of inpatient rehabilitative treatment predicted their achieved functional recovery five weeks later, independently of the degree of physical impairment (see Supplementary Material for further details of the Methods and Results). This validation analysis thus confirmed that the drive ratings used for classification in the current study were clinically meaningful.

Exclusion criteria for both groups included severe cognitive impairment, aphasia, and isolation due to colonization with multidrug-resistant organisms. Furthermore, we matched DI and control patients for age, gender, and degree of impairment in activities of daily living (i.e., severity) quantified by the Barthel-Index (Lübke et al., 2004; Mahoney & Barthel, 1965). In total, out of the 465 patients that were screened for eligibility, n = 77 fulfilled the inclusion criteria for the DI group (i.e., showed no or little drive during therapy and daily life activities), and n = 388 fulfilled the inclusion criteria for the control group (i.e., were matched to DI individuals for age, gender, and Barthel-Index score). Eventually, 30 patients from each group completed the follow-up (see Supplementary Fig. S1 for a detailed description of the screening and recruitment process). All patients provided written informed consent, and the study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Medical Faculty of the Heinrich Heine University of Düsseldorf (protocol no 2017014131).

2.2. Procedure

Patients were tested in a single behavioural testing session. Each session lasted approximately 60 min. The patients completed an effort-based decision-making task and self-report questionnaires assessing symptoms of depression and apathy.

2.3. Effort-based decision-making task

To investigate the willingness to exert effort in return for rewards, patients performed a task which was previously used in healthy volunteers and patients with neurological diseases (Bonnelle et al., 2015; Chong et al., 2018; Le Heron et al., 2018b; Saleh et al., 2021b). At the beginning of each experimental session, each participant's individual maximum voluntary contraction (MVC) was assessed by asking the subjects to grip a handheld dynamometer (Vernier, Orlando, USA) as strongly as possible with their preferred (non-affected) hand. The MVC was calculated by measuring the highest force exerted over three contractions. Then, patients performed a training session to be familiarized with the force required to reach each effort level. On each trial, patients were presented with an image of an apple tree (Fig. 1) that combined information about the obtainable reward (number of apples) and the required physical effort (vertical position of a bar on the trunk of the tree). Patients could either accept or reject the offer and indicated their choice by pressing a “yes” or “no” key of an external computer keyboard.

Accepting an offer resulted in a 5 s window to squeeze a handheld dynamometer to reach the required effort level and maintain the required force for at least 1 s. During this effort production period, a bar that filled the trunk as patients squeezed gave on-line visual force feedback. Successful trials were followed by a feedback phase visualizing the reward earned during the trial. If subjects failed to reach the denoted level or did not maintain the required force continuously for at least 1 s, no apples were gathered. In contrast, rejecting an offer led to a 5 s pause announcing the upcoming trial. To prevent strategic behaviour and temporal discounting effects, all blocks and trials lasted for the same duration, regardless of the previous choice. Importantly, patients had to squeeze after every accepted trial, thus no hypothetical choices were made. Five possible reward levels (2, 4, 8, 12, or 16 apples on the tree), and five possible effort levels (10 %, 27.5 %, 45 %, 62.5 %, or 80 % of the individually determined MVC) were used. Each reward and effort combination (5 x 5 = 25) was sampled a total of four times in a randomized order, adding up to a total of 100 trials split into four blocks consisting of 25 trials each. Patients were instructed to “collect” as many apples as possible by trading off the reward (number of apples) against the cost (the required effort level).

Based on task performance, they received a flexible payment consisting of 0.5 cents for each apple collected. We chose to use real instead of hypothetical payouts due to differences between choices made in hypothetical versus real settings (Camerer & Mobbs, 2017; Galotti, 2007). To reduce fatigue effects, a break of three to five minutes was introduced after each block. These breaks were used to fill out the questionnaires. For each trial, choice (accept/reject), success in performing the required effort (success/fail), decision latency, duration of force, and accomplished force (in Newton), as well as deviations from the effort demand (in Newton and percent), were recorded. To assess participants' subjective effort perception, we asked them to rate the perceived physical demand of each effort level on a 21-point visual rating scale at the end of the experiment, ranging from 0 (*not demanding at all*) to 20 (*extremely demanding*).

2.4. Questionnaires

Patients were administered two depression and apathy questionnaires: the depression subscale of the Hospital Anxiety and Depression Scale (*HADS*) (Petermann, 2011; Zigmond & Snaith, 1983) and the depression subscale of the 21-item version of the Depression Anxiety Stress Scales (*DASS*) (Antony et al., 1998; Lovibond & Lovibond, 1995). Patients were also asked to complete the German versions of the Apathy Evaluation Scale (*AES*) (Lueken et al., 2006; Marin et al., 1991) as well as a German translation of the Apathy Motivation Index (*AMI*) (Ang et al., 2017). These questionnaires have been extensively validated in clinical cohorts in previous research, with good internal consistency, reliability, specificity, and sensitivity results (Ang et al., 2017; Lueken et al., 2006, 2007; Osman et al., 2012). The questionnaires were completed during the breaks between the experimental blocks. Cronbach's alphas for the total scales of AES, AMI, HADS, and DASS were determined $\alpha = 0.87$, $\alpha = 0.71$, $\alpha = 0.67$, and $\alpha = 0.88$ respectively.

2.5. Analyses of behaviour and questionnaires

As a general measure of task performance, we calculated the proportion of accepted (acceptance rate) and successfully completed accepted trials (success rate) and compared them between groups using non-parametric Mann–Whitney *U* test (due to non-Gaussian distribution of the data: Shapiro-Wilk, $p < 0.05$ for acceptance and success rate). To test whether the patient groups differed in terms of how their choices and success were governed by reward and effort levels, we conducted two generalized linear mixed effects models with a logistic link function (to account for the binomial distribution of the data), using the *glmer* function from the *lme4* package in R (*lme4* Version 1.1.26; Bates et al.,

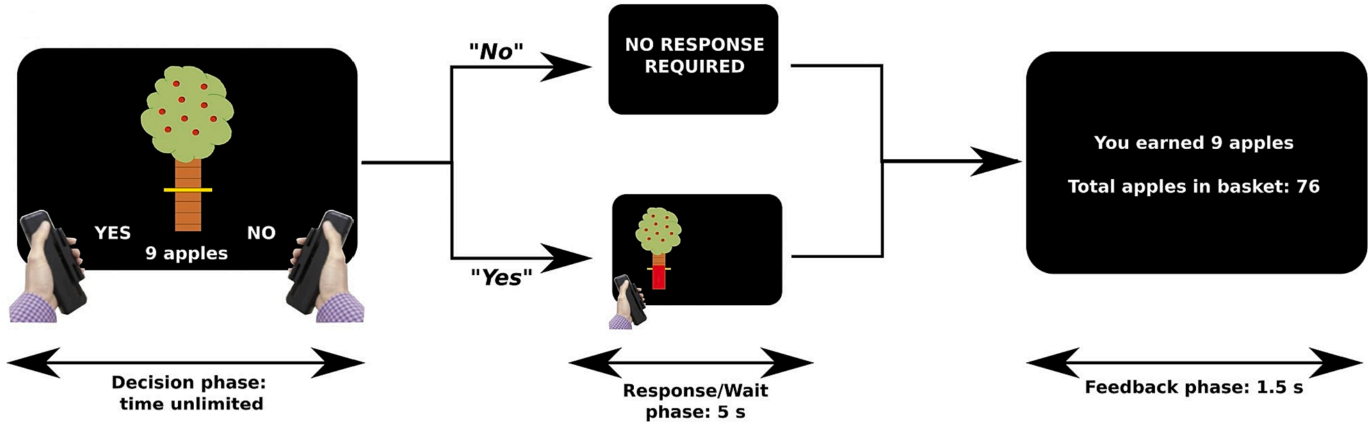

Fig. 1. On each trial, participants were presented with an image of an apple tree that combined information about a monetary reward available (number of apples) in return for physical effort required to exert (vertical position of a bar). Patients could either accept (“Yes”) or reject (“No”) each offer. After accepting an offer, participants had to perform the required effort (adjusted to the maximum force) and maintain the force for at least 1 s, while rejecting an offer led to a short pause. From Le Heron et al. (2018).

2015). These functions included either choice (accept versus reject) or success in performing the required effort (success versus fail) as a binary outcome variable, and fixed effects of effort level, reward level (both continuous), group (categorical), and their interactions.

Additionally, the models contained a random effects structure of subjects and both task-associated variables (i.e., reward and effort level). Categorical responses were coded as binary values and continuous variables were grand mean-centered. To disentangle the dissociable effects of reward and effort sensitivity, i.e., to which degree the choices were affected by variations in reward and effort levels, respectively, we specifically evaluated the following interaction effects: (i) Effort x Group, (ii) Reward x Group, and (iii) Effort x Reward x Group.

In addition, to test whether variations in effort-based decision making can be explained by differences in apathy or depression severity, we repeated the exact same analysis as above twice, but now, instead of categorizing patients as drive-impaired or non-impaired, we grouped them according to (a) apathy and (b) depression state based on questionnaires. Assignment to the apathetic/non-apathetic or depressed/non-depressed group was performed according to clinical cut-off values. Patients were determined as *apathetic* when either of the two self-rating scores reached the cut-off value (n apathetic = 31 vs. n non-apathetic = 29). The same logic was applied to identify *depressed* individuals (n depressed = 13 vs. n non-depressed = 47). Comparisons of questionnaire results were performed with a two-sample unpaired t-test, or Mann–Whitney U test, depending on the variable type. Questionnaire scores were entered as continuous variables. Bonferroni correction was applied to correct for multiple comparisons. Self-reported ratings of the perceived effort demand were analysed using a mixed-model ANOVA with rating as dependent variable, group as a between-subject variable, and effort level as a within-subject variable.

Finally, in a supplementary analysis, we explored whether behaviour on the effort-based decision-making task, as quantified by acceptance and success rates, was associated with a specific pattern of brain damage using voxel-based lesion-behaviour mapping (VBML; see Supplementary Material for an extended description of the applied methodology).

3. Results

3.1. Patient characteristics and questionnaire results

The two groups were matched on gender, age, type of stroke, and Barthel-Index. Demographics, clinical background variables, and descriptive statistics are presented as means and standard deviations in Table 1. Notably, there were no significant differences between DI and control individuals in apathy scores (as measured on AES and AMI) or depression scores (as measured on DASS and HADS).

3.2. Drive impaired patients differ in effort performance, but not in accept/reject choices

We first compared patients' willingness to engage in effortful trials, indexed by the overall percentage of trials accepted (acceptance rate). This did not reveal any significant differences between DI and control individuals (82.9 % ± 2.97 and 81.4 % ± 3.74 for DI and control patients, respectively, $z = -0.517$, $p = 0.605$). Next, we used logistic regression to assess how patients' trial-by-trial choices depended on reward and effort level, and whether this differed between patient groups. This analysis showed a significant effect of reward ($b = 0.519$, $z = 5.121$, $p < 0.001$) and effort ($b = -5.763$, $z = -4.029$, $p < 0.001$), but neither a significant main or interaction effect of group (Group: $b = 0.057$, $z = 0.882$, $p = 0.949$; Group × Effort: $b = 2.649$, $z = 1.603$, $p = 0.109$; Group x Reward: $b = -0.085$, $z = -0.648$, $p = 0.517$; Group x Reward x Effort: $b = -0.198$, $z = -0.931$, $p = 0.352$, Fig. 2). This indicates that patients' choices were sensitive to both reward and effort levels, but also that these effects did not differ between groups.

Contrary to our expectations, and unlike findings of previous studies using the same paradigm but in patients with Parkinson's disease and small vessel cerebrovascular disease (Le Heron et al., 2018a, 2018b; Saleh et al., 2021b), a substantial proportion of our sample did not show any effort discounting at all. In other words, they accepted all offers irrespective of effort and/or reward level (10 subjects (33.3 %) in the DI group and 8 subjects (26.6 %) in the control group). A post-hoc chi-square test comparing the number of such individuals did not show any significant group difference ($\chi^2 = 0.318$, $p = 0.573$). Hence, this behaviour does not appear to be associated with drive state. To ascertain that our pattern of results did not depend on this particular behaviour, we re-ran the same analyses as described above, while excluding individuals that accepted all offers. This analysis yielded the same pattern (no significant differences between groups in terms of choice behaviour, Supplementary Tables S1 and S2).

Table 1
Demographics, clinical background data, and questionnaire scores.

	DI group ($n = 30$)	Control group ($n = 30$)	Group comparison	
			χ^2/T	p
Gender (*n, %*)				
Female	13 (46.7)	12 (46.7)	0.07	0.793
Male	17 (53.3)	18 (53.3)		
Age (*M, SEM*)	71.76 (1.54)	74.07 (1.57)	−0.84	0.407
Barthel-Index (*M, SEM*)	50.17 (1.26)	59.50 (1.38)	−1.59	0.117
Age (*M, SEM*)	71.76 (1.54)	74.07 (1.57)	−0.84	0.407
Days since stroke (*M, SEM*)	40.57 (4.44)	41.56 (3.56)	0.18	0.861
Diagnosis (*n, %*)				
Ischemic stroke	28 (93.33)	26 (86.67)	0.74	0.389
Hemorrhagic stroke	2 (6.67)	4 (13.33)		
Questionnaires (*M, SEM*)				
DASS-21	5.17 (0.36)	4.03 (0.32)	0.96	0.339
HADS-D	7.10 (0.46)	4.97 (0.39)	2.34	0.061
AES	14.50 (0.65)	12.90 (0.62)	0.74	0.461
AMI				
Total Score	24.55 (0.89)	23.40 (0.88)	0.526	0.601
Behavioural	5.38 (0.39)	5.57 (0.39)	−0.20	0.839
Social	11.10 (0.59)	10.73 (0.59)	0.30	0.766
Emotional	8.07 (0.51)	7.10 (0.47)	1.08	0.281

Note. DASS-21 = depression subscale of the Depression Anxiety Stress Scales (clinical cut-off ≥ 10), HADS-D = depression subscale of the Hospital Anxiety and Depression Scale (clinical cut-off ≥ 8), AES = Apathy Evaluation Scale (clinical cut-off ≥ 18), AMI = Apathy Motivation Index.

Next, we repeated the same analyses as above, but now using success (reward attained or not) instead of choice as the dependent variable of interest. On average, patients performed the required force and therefore obtained the reward in 83.9 % of accepted trials. There was a significant group difference, with the DI group achieving the required effort on lower percentage of accepted trials compared to controls (79.8 ± 3.09 and 88.0 % ± 2.43, mean ± SEM for DI and controls, respectively, $z = -2.004$, $p = 0.045$). These results show that despite accepting effort-requiring offers as often as control patients, DI patients actually performed the required instrumental effort less consistently. The results of the logistic regression further corroborated these findings. Success rates were related to effort, but not reward level (Reward: $b = 0.029$, $z = 1.259$, $p = 0.208$; Effort: $b = -6.442$, $z = -7.925$, $p < 0.001$). Notably, there was no interaction effect of group (Group × Effort: $b = -0.172$, $z = -0.161$, $p = 0.872$; Group x Reward: $b = 0.014$, $z = 0.495$, $p = 0.620$; Group x Effort x Reward: $b = -0.143$, $z = -1.350$, $p = 0.177$), but a main effect of group ($b = -0.885$, $z = -2.095$, $p = 0.036$; Fig. 2). Together, this indicates that reduced success rates in DI subjects are not due to an increased sensitivity for efforts or a decreased sensitivity for rewards; but rather due to a lack of execution of the willingness to engage in effortful activities and short-term perseverance with effortful activities. This lack of effort execution and perseverance is observed across all levels of effort and is not limited to high efforts alone.

Voxel-based lesion-behaviour mapping did not find any statistically significant associations between lesion location and acceptance rate or success rate across both groups.

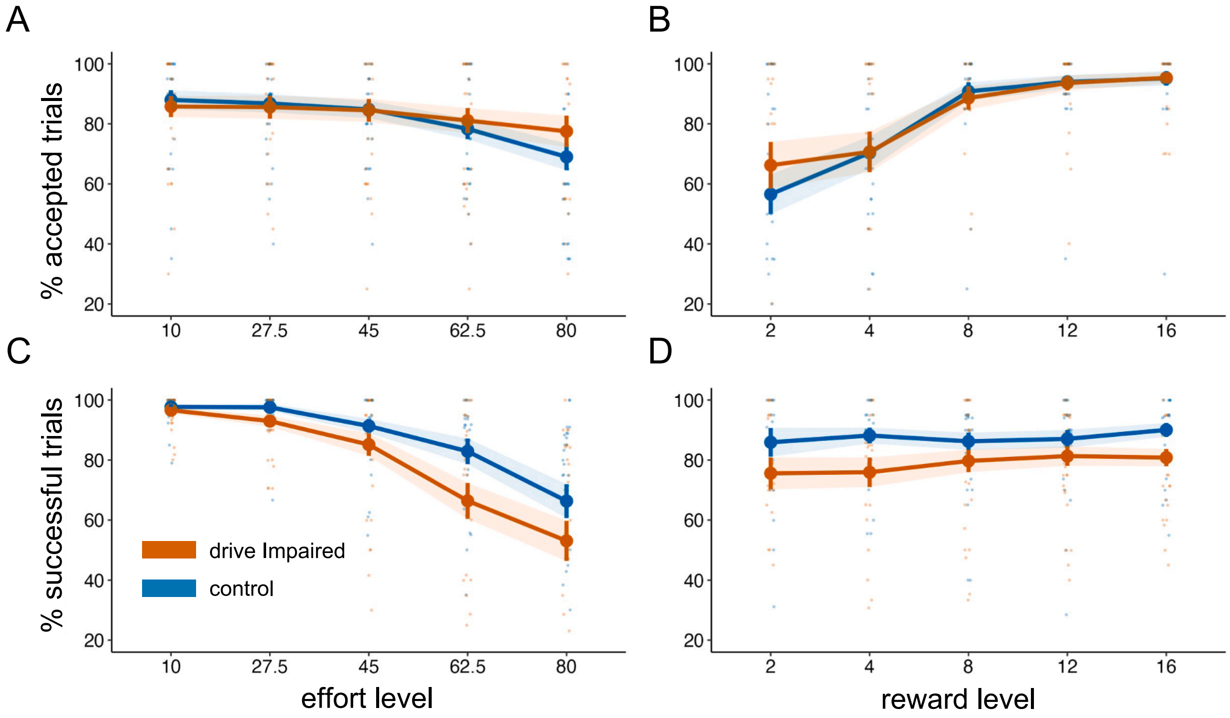

Fig. 2. Averaged acceptance and success rates are plotted as functions of effort (A, C) and reward (B, D). Acceptance rates decrease as a function of effort (A) and increase as a function of reward (B), with no significant group difference. However, after accepting an offer, DI individuals fail significantly more often, compared to their unaffected counterparts (C, D). Effort levels are presented as proportions of the individually calibrated MVC. Bold (light) dots represent the group (single-subject) mean, error bars and shaded areas represent standard error of the mean.

3.3. *DI individuals appear to lack perseverance, not strength*

The finding that DI patients are more likely than controls to fail to perform the required instrumental effort may be caused by two factors. To successfully complete a trial after accepting an offer, patients have to pass two binary criteria: First, they must exceed the required effort (produced force; e.g., 80 % of MVC). Second, they have to maintain this force for at least 1 s (persistence). We therefore applied the same logistic regression model as above, with *produced force* and *persistence* as binary dependent variables. Fig. 3 illustrates the proportion of participants who successfully achieved either of the two criteria across varying levels of effort. There were no significant effects of group on produced force (Group: $b = -0.416$, $z = -0.822$, $p = 0.411$; Group x Reward: $b = 0.031$, $z = 0.830$, $p = 0.406$; Group x Effort: $b = -1.303$, $z = -0.825$, $p = 0.409$; Group x Effort x Reward: $b = -0.167$, $z = -1.162$, $p = 0.245$). In contrast, however, we found a significant main effect of group on persistence ($b = -0.937$, $z = -2.250$, $p = 0.025$), without any significant interactions (Group x Reward: $b = -0.013$, $z = -0.069$, $p = 0.945$; Group x Effort: $b = 0.151$, $z = 0.689$, $p = 0.491$; Group x Effort x Reward: $b = -0.035$, $z = -0.208$, $p = 0.835$). Notably, both variables were modulated by effort

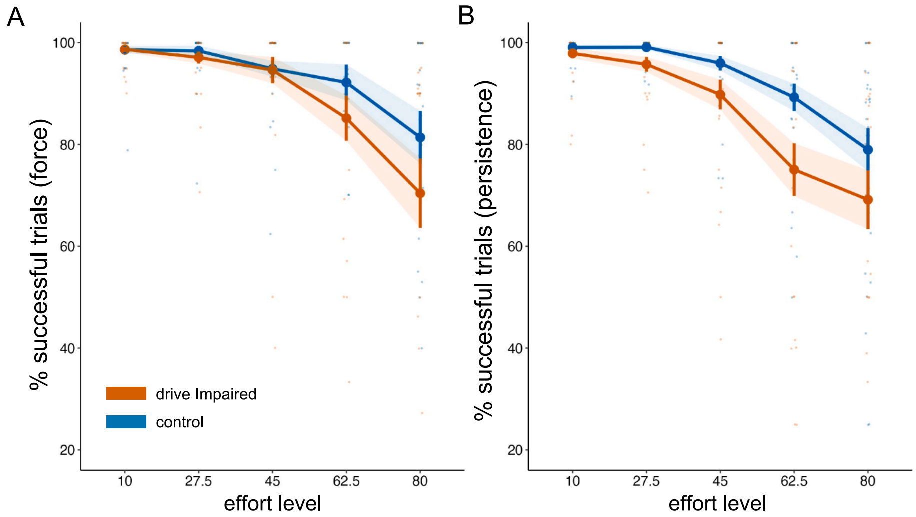

Fig. 3. Patient's performance in the physical effort task, illustrated by the averaged proportion of participants who met each criterion. (A) Across groups, individuals did not differ in their ability to achieve the necessary effort threshold. (B) However, we found a significant group difference in the capability to maintain the force over the target level for at least one second. Effort levels are presented as proportions of the individually calibrated MVC. Bold (light) dots represent the group (single-subject) mean, error bars and shaded areas represent standard error of the mean.

(Effort [produced force]: $b = -4.673$, $z = -4.119$, $p < 0.001$; Effort [persistence]: $b = -1.510$, $z = -9.063$, $p < 0.001$), but not by reward (Reward [produced force]: $b = 0.010$, $z = 0.388$, $p = 0.698$; Reward [persistence]: $b = 0.259$, $z = 1.677$, $p = 0.094$). Together, these results indicate that both groups did not differ in their ability to reach the required force demand. Instead, after reaching the force level, DI patients failed to hold and maintain the effort production more often than control patients, indicating a lack of short-time perseverance with effort. This lack of perseverance in force production occurred across all effort levels.

This finding raises questions about their understanding of the task requirements, specifically the need to sustain the effort for more than 1 s. To address this concern, an additional analysis was conducted, including block and the interaction between block and group as predictors. A Group x Block interaction would indicate that the two groups differed in their initial understanding of the task and potentially showed different patterns of performing the task over time (i.e., learning to maintain effort production for a certain duration). However, the interaction effect did not reach statistical significance (Group x Block: $b = 0.023$, $z = 0.190$, $p = 0.850$), suggesting that the groups did not differ in their understanding of the task requirements or in their learning patterns throughout the task. More detailed information on this analysis, along with supplementary analyses of task performance, are presented in the supplementary material (Supplementary Table S3 and Supplementary Figure S2 and S3). Notably, voxel-based lesion-behaviour mapping did not reveal statistically significant associations between lesion location and perseveration across both groups.

Finally, we asked patients to rate their subjective perception of effort. While both groups reported increased subjective perception with increasing effort levels, this did not differ between groups (Supplementary Figure S4).

3.4. Effects of depression and apathy on behavioural responses

While we did not find any significant effects of the depression state on behavioural responses, differences in the apathy state (i.e., an apathy score in the clinical range) were associated with changes in terms of choice behaviour. Our analyses revealed a significant two-way interaction between reward and apathy state upon accept/reject choices ($b = -0.340$, $z = -2.750$, $p = 0.006$), that was primarily driven by apathic patients accepting more offers with low rewards than non-apathic patients. These findings indicate altered processing of reward magnitude on decisions about engaging or not in effortful actions. In other words, patients that were less motivated according to self-reported apathy questionnaires displayed a reduced sensitivity to changing rewards (Fig. 4). There were no differences in performance between either depressed vs. non-depressed or apathetic vs. non-apathetic patients. A full table of these analyses and the corresponding results is presented in the Supplementary Material (Supplementary Table S4 – S7).

4. Discussion

Functional recovery after stroke requires motivation to engage in physically demanding rehabilitative training. Unfortunately, reductions in motivation and drive during rehabilitative training are not uncommon post stroke, with mechanisms underlying reduced persistence in effortful training still being elusive. Gaining a deeper understanding of deficits is crucial for enhancing functional rehabilitation strategies and optimizing outcomes for stroke patients.

Therefore, we aimed to investigate decision-making mechanisms underlying effort-based choices in stroke patients, comparing those with and without reduced drive, initiation, and endurance during rehabilitation training, according to their treating rehabilitation specialists. To this end, we used a behavioural probe of effort-based decision making outside of the direct therapy context. We found that stroke patients that demonstrated low drive and persistence during rehabilitative training did not differ from control patients in terms of their willingness to accept or reject an effortful offer. Instead, after choosing to engage in an effort-requiring option, those patients were more likely to fail the physical effort demand – not because of an inability to achieve their target, but because of a lack of persistence in effort production.

Taken together, stroke patients with apparent drive impairments during rehabilitative therapy were just as willing as patients without motivational impairments to commit to effort production for a certain

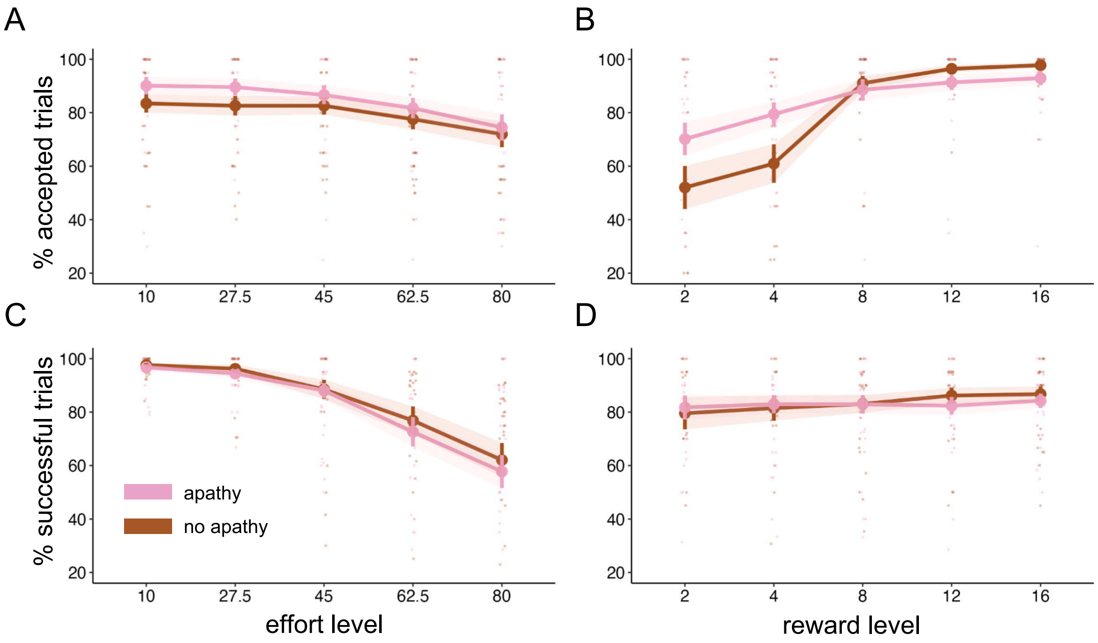

Fig. 4. Averaged acceptance and success rates as functions of effort (A, C) and reward (B, D) for apathetic and non-apathetic patients. Success rates (C, D) did not differ between the two groups, whereas choice rates in the apathy group reveal a reduced sensitivity to changing reward levels. Effort levels are presented as proportions of the individually calibrated MVC. Bold (light) dots represent the group (single-subject) mean, error bars and shaded areas represent standard error of the mean.

reward during the choice phase. However, after choosing an effort-requiring prospective reward, they did not maintain the required effort challenge to actually reap the reward during the action phase, suggesting a discrepancy between expectation and performance. Consequently, motivation and goal-directed decision making can be conceptualized as behaviour that does not solely involve the decision about engaging in a physical act or not, but also the performance resulting from the decision. Indeed, motivation is defined as a force or energy that activates, directs, and sustains a given behaviour (Hebb, 1955; Kleinginna & Kleinginna, 1981; Studer & Knecht, 2016). In line with that, a recent neurocognitive framework of cost-benefit decision making defines three different phases of goal-directed motivation: (a) choosing whether to act or not, (b) persisting with the chosen behaviour, and (c) learning about the outcome (Le Heron et al., 2018c).

Intriguingly, our results suggest that these different dimensions of goal-directed motivation and behaviour can be affected selectively. Functional neuroimaging studies in healthy individuals indicate that all three phases are supported by the ventral striatum and the anterior cingulate cortex, and deficits in goal-directed behaviour observed across different brain disorders appear to be linked to disruptions of functional networks involving these two core regions (Le Heron et al., 2018c). In our stroke sample, voxel-based lesion-behaviour mapping did not reveal a specific localised neural correlate for the failure to execute effort-based choices, as operationalised in the success rate. This null finding may suggest that the behaviour is driven by a functional network rather than a single localised area that can be detected using VBLM (see e.g., Karnath et al., 2018). Alternatively, it could be due to the lesion overlap in our sample size being on the lower end of the threshold required to obtain reliable statistical results (Lorca-Puls et al., 2018). Future research may aim to elucidate the neurocomputational mechanisms underlying the observed selective change in effort execution.

Drive-impaired stroke patients appear to be affected uniquely in the persisting phase of effortful behaviour, even on the very short time scale of the trials of our paradigm. Such a reduced ability to maintain physical effort, even after choosing to produce this effort, could be a possible explanation for clinical observations of reduced drive, initiation, and endurance during functional rehabilitative therapy and training of activities of daily living. As perseverance in training programs is a crucial part of successful rehabilitation after stroke, a reduced ability to maintain goal-directed effort could ultimately limit patients' functional recovery and – in the long term – the quality of life (Danzl et al., 2012; Paolucci et al., 2012). Moreover, patients showing this type of behaviour may be falsely diagnosed as being depressed, since impaired drive and reduced persistence in completing tasks or activities are common symptoms of depression (Tay et al., 2021). We found no systematic differences in self-reported depression symptoms between our two patient groups.

In contrast to our hypothesis, patients who were identified by their rehabilitation specialists as showing diminished drive, initiative, and perseverance did not differ from unaffected control patients in terms of self-reported ratings of apathy. These results suggest a potential distinction between behavioural patterns that are captured by questionnaires versus those perceived by clinical professionals, and indicate that self-report apathy questionnaires might be unsuitable to identify all individuals that are at risk of reduced participation and persistence with rehabilitative training. It is plausible that the deficits observed in those patients, which primarily manifest during the persistence phase of goal-directed behaviour, may not be fully captured by the self-report questionnaires and their sub-scales used in our study. These questionnaires primarily assess global apathy levels and may not detect specific deficits in maintaining certain effortful behaviours over time. Additionally, as the questionnaires rely on self-reporting, there is a possibility of a lack of insight into one's own motivational impairments. Patients with impaired drive might exhibit reduced awareness or insight into their own deficits, leading to potential underestimation of their condition when relying solely on self-reported measures. Future research may test if deficits in persisting with a certain behaviour may be a latent dimension of apathy that prevails independently and requires new questionnaires and instruments to be captured.

Self-reported apathy ratings were also not associated with any systematic changes in effort persistence on our task in our samples. However, apathy scores (measured with the AES and AMI) were linked to a reduced reward sensitivity when deciding about acting or not, such that patients with higher levels of apathy showed a reduced sensitivity for changing reward levels and a higher propensity to accept low reward options compared to non-apathetic patients. This result contrasts with previous work who found an apathy-related *decrease* in acceptance of low reward offer in Parkinson's and cerebral small vessel disease (Le Heron et al., 2018a, 2018b; Saleh et al., 2021b). Given that this is the first study in stroke patients, further research will be needed to determine if our result is coincidental or reflects a true, potentially disease-driven difference.

Some limitations of the current study should be noted. First, as mentioned above, a considerable number of patients in both groups did not show any effort discounting at all. These patients accepted each offer that was presented, regardless of reward or effort level. Interestingly, the same behavioural pattern was also reported in a recent study investigating effort discounting in healthy controls and people with schizophrenia and major depressive disorder (Cathomas et al., 2021). In that study, a lack of effort discounting was present in both clinical groups, but not in control participants. Like the current study, these clinical groups were tested during in-patient treatment. Thus, one conceivable explanation is that the lack of effort discounting was driven by a social desirability effect driven by the treatment environment. Our patients may have unconsciously considered the experiment as a part of their treatment, given that it took part during and in direct relationship to their rehabilitation program. Therefore, the tendency to accept all presented offers could be seen as a result of a behavioural approach that aims to meet hypothetical requirements of participation and commitment. As we did not directly measure impulsive behaviour in our sample, it also remains possible that this choice pattern is based on alterations in impulse control and/or response inhibition. This potential link warrants further exploration in future studies. Another limitation of our study is related to the definition of *drive-impaired* stroke patients, as it is not a validated construct but rather based on subjective evaluations provided by clinicians. However, it is worth noting that these observations are robust due to the extensive experience, interdisciplinary exchange, and expertise of the clinical staff who made them. By regularly monitoring and evaluating patients' behaviour, clinical staff can provide a comprehensive and nuanced understanding of their deficits. Moreover, our independent validation study confirmed that these ratings had clinical validity by demonstrating that they predicted the functional recovery achieved by patients through rehabilitative training. Further, our task design included money, a secondary and extrinsic reward, as an incentive. Hence, the generalizability of the results to intrinsic benefits (such as positive feelings experienced through successful participation) may be limited. Finally, a supplementary voxel-based lesion-behaviour mapping on the structural brain scans acquired as part of clinical routine did not reveal the neural substrates of impaired drive after stroke. In samples similar to ours, functional neuroimaging during an effort-based decision-making task may provide more insights into the precise neurocomputational underpinnings.

To our knowledge, this is the first study to characterize behavioural mechanisms that underlie perceived disruptions in drive, initiation, and persistence during rehabilitative training among stroke patients. Through use of value-based and effort-based decision-making paradigms, doctors and therapists may be able to reveal, classify, and quantify different domains of motivation that cannot be captured by self-report questionnaires, diagnostic manuals, and judgments alone, and develop new and individualised motivational approaches to be employed by neurorehabilitative specialists. Revealing the processes and phases that underlie aberrant goal-directed behaviour could therefore serve as a novel and promising new approach to eventually customize individual therapies for rehabilitation patients.

5. Conclusions

Stroke patients that show reduced drive, initiation, and endurance during neurorehabilitative therapy do not differ from control patients in terms of committing to effortful behaviour. Instead, they are characterized by deficits in maintaining the physical effort force for the required time, even after accepting to perform that action. Notably, this altered behavioural dimension of goal-directed activity was not captured by apathy questionnaires, but clinical observation only. These findings underscore the clinical significance of assessing and addressing persistence deficits in stroke patients, as they may provide valuable insights for optimizing neurorehabilitative therapies and enhancing functional recovery.

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CRediT authorship contribution statement

Mani Erfanian Abdoust: Formal analysis, Investigation, Visualization, Writing – original draft. **Stefan Knecht:** Conceptualization, Methodology, Project administration, Writing – review & editing. **Masud Husain:** Resources, Writing – review & editing. **Campbell Le Heron:** Resources, Writing – review & editing. **Gerhard Jocham:** Investigation, Writing – review & editing. **Bettina Studer:** Data curation, Funding acquisition, Project administration, Software, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bandc.2023.106123.

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