

Motivation–cognition interaction: how feedback processing changes in healthy ageing and in Parkinson’s disease

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Abstract

Background Several studies have investigated the interaction between motivation and cognition in both young and older adults, but with inconsistent results. A recent hypothesis suggests exploring the role of dopamine to study this interaction.

Aims To explore how different motivational states can modulate cognitive control, as well as investigate the hypothesis of a dopaminergic role in this phenomenon.

Methods 27 young subjects, 15 healthy old subjects, and 15 Parkinson’s disease (PD) patients took part in this study. The motivational Simon task—a new paradigm in which rewards and punishments are delivered to promote fast and accurate responses—was employed. The participants’ performance was evaluated by analysing their reaction times and accuracy, while employing a diffusion model analysis.

Results The employment of positive and negative feedback significantly modulated performance in a conflict task. In both, the young and older participants, the speed–accuracy trade-off significantly changed in response to different motivational incentives ($p < .005$), although in opposite ways. On the contrary, PD patients showed an absence of performance modulation in response to positive and negative feedback.

Discussion and conclusions In normal conditions, motivation interacts with cognitive control to modulate decisional aspects of a response in a conflict task. The elderly modulate their performance in response to positive and negative feedback differently from young adults, showing a classical positivity effect. The impairment manifested by PD patients, which is compatible with the literature about feedback processing deficits in this clinical condition, can support the hypothesis that the interaction between motivation and cognitive control is mediated by dopaminergic functionality.

Keywords Cognitive control · Motivation · Parkinson’s disease · Reward · Punishment · Diffusion model

Introduction

The human ability to focus one’s attention on relevant information and to simultaneously neglect irrelevant information is a crucial topic in cognitive psychology. This ability is called cognitive control and is thought to originate from a dedicated cognitive mechanism that coordinates goal-driven behaviour [1]. Cognitive control is considered a high-level process that is commonly included in executive functions (EF), due to its association with prefrontal cortex (PFC) activity [2]. One function of cognitive control is to adapt the cognitive system to different environmental situations; this adaptation is usually driven by the detection of cognitive conflict [3], i.e., a situation of interference between relevant and irrelevant stimuli. In cognitive psychology, different conflict tasks have been designed to study cognitive control: a common feature of these tasks is the presence of irrelevant information that slows down the processing of relevant information. In the

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Simon task, participants are required to respond to the colour of the stimuli by pressing the left or right keys. Although the response location is irrelevant to the task, the responses are faster and more accurate when the stimulus and response location correspond, i.e., in corresponding (C) trials, than when they do not correspond, i.e., in non-corresponding (NC) trials. The difference between responses to C and NC trials is called the Simon effect [4]. Despite this traditional structure of conflict tasks, it is generally recognised that cognitive control is not only involved in situations involving cognitive interference and conflict, but also “invoked” in emotional situations such as danger [1, 5]. For this reason, many variants of the classical conflict tasks have been proposed, with the aim of exploring the interaction between affect and cognitive control [6–17].

Most of these studies had the objective of investigating the role of emotional manipulations on cognitive control. By creating situations of emotional conflict or introducing emotional stimuli during the execution of classical tasks, several studies have tried to evaluate whether these emotional variables might influence different aspects of conflict processing, by exploring the interactions between emotional stimuli, as well as positive or negative valence and the recruitment of attentional resources. At the same time, recent works have explored the role of motivation on cognitive control: in most of these studies, motivation was manipulated using low and high reward cues, which are commonly considered to be motivational incentives, or stimuli that activate the motivational system [8, 13, 18–21].

However, the inconsistent results obtained in these studies make the interaction between cognitive control and motivation a phenomenon that is still not well understood. One hypothesis to explain the different results obtained concerns the neural mechanism underlying the interaction between motivation and cognitive control, by detailing the role of dopamine [22–24].

In fact, in the system involved in implementing cognitive control, which is mainly represented by the anterior cingulate cortex (ACC) and the dorsolateral PFC, an important modulatory function is played by the ventromedial striatal dopaminergic system [25]. Dopamine (DA) and, moreover, the ventromedial striatal dopaminergic system are known to be critical for successful feedback processing [26–28] and motivated behaviour, with motivation intended to be what makes one work to obtain a reward or avoid a punishment [29]. Studies in animals and humans have showed that while positive feedback, such as rewards, triggers a phasic increase of DA levels in the midbrain, negative feedback like punishments cause a dip in DA: these different responses modulate ACC activity, which in turn may regulate motivation and learning processes [30, 31].

After linking all of this evidence, it is clear that the functionality of the dopaminergic system represents a critical variable in how motivation modulates cognitive control. Following this direction, a recent study has explored the interaction between reward processing and cognitive control by accounting for the functionality of the dopaminergic striatal system [32]. In detail, Aarts and colleagues [32] have showed that the introduction of rewards in a cognitive control task produces different effects, depending on the baseline levels of DA synthesis capacity in the striatum: while the introduction of rewards enhanced performance in people with low baseline DA levels, a detrimental effect of rewards in a cognitive control task was manifested by people with a high baseline capacity for DA synthesis [32]. The results of this study seem to support the hypothesis of a mediating role by dopaminergic transmission in the interaction between motivation and cognitive control.

In the current study, we want to add knowledge about how motivation interacts with cognitive control in the normal condition, as well as explore this dopaminergic hypothesis. To do so, we tested young and older healthy subjects, as well as Parkinson’s disease patients. We wanted to investigate the interaction between motivation and cognitive control in normal conditions and in two conditions where the dopaminergic striatal system goes through significant changes: healthy ageing and Parkinson’s disease (PD). Basing on the evidence that reported a main age-related loss in various biochemical markers of the nigrostriatal dopaminergic system [33], we consider healthy ageing a condition involving the physiological decline of dopaminergic functionality. On the other hand, PD is a condition of pathological dopaminergic decline that, in some cases, turns in a condition of dopaminergic “dysregulation”. In fact, although PD is initially caused by DA loss in the striatum, the functionality of the dopaminergic system in PD patients is also influenced by pharmacological treatment, which in most cases consists of DA replacement therapy (DRT). More specifically, in PD, the reduction of dopaminergic neurons is more pronounced in the dorsal part of the striatum, with respect to the ventral part; this different state of dopaminergic depletion can bring about differential effects of DRT on the neural circuits that involve these regions. In this way, while DRT can restore DA levels in the dorsal fronto-striatal system, an overstimulation can also take place in the ventral fronto-striatal system at the same time, causing a state of dopaminergic dysregulation [34]. To investigate if and how a dopaminergic dysfunction affects the interaction between motivation and cognitive control, in the current study, we asked healthy young and elderly participants, as well as medicated PD patients, to perform the motivational Simon task. In this task, a classical Simon paradigm was modified

by introducing two virtual performance-contingent types of feedback, rewards and punishments, presented as motivational incentives to promote fast and accurate responses. To better explore this phenomenon, we analysed the performance of these three groups by adopting the diffusion model analysis [35], which is a method to explore both the perceptual and decisional components of their performance.

Method

Participants

Fifty-seven participants were recruited for this study: 27 young subjects (8 male, age range 20–35 years, mean 24.7, SD 3.4), 15 old subjects (4 males; age range 48–81 years; mean 68.1, SD 9.6), and 15 PD patients (6 males; age range 49–85 years; mean 71.8, SD 8.7). We evaluate an adequate sample size, as determined by performing a power analysis using G*Power [36], which recommended testing at least 15 subjects for each group, with a power ($1 - \beta$ error probability) of 0.95.

The inclusion criteria for this study were participants with normal or corrected-to-normal vision. The exclusion criteria applied for the recruitment of the young and old healthy participants were the presence of neurological disease (any medical conditions associated with a head injury, epilepsy, or stroke), reported history of psychiatric disorders or neurological disease, and the use of psychiatric and neurological medications. Additionally, for both the PD patients and old subjects, the exclusion criterion was a Mini-Mental State Examination [37] score under the cut off of 24.

The PD patients fulfilled the diagnostic criteria for PD, according to the PD Society Brain Bank Criteria [38]. The mean disease duration was 5.1 years (range of onset 2–13 years, SD 3.8), and the PD patients had a mean estimated motor sub-score of 22.13 (range 8–39, SD 10.2) on the Unified Parkinson's Disease Rating Scale (UPDRS) Part III [39]. The patients were asked to continue taking their medication at the required time on the day of testing. Six patients received dopamine precursors (levodopa), four patients received dopamine agonists, three patients received a monoamine oxidase inhibitor (MAOI), and two

patients were taking a combination of levodopa and dopamine agonists. The old participant and PD patient groups were matched for age, gender, and education (Table 1).

Written informed consent was obtained from all of the participants. The study was carried out in accordance with the provisions of the World Medical Association Declaration of Helsinki and was approved by the Ethics Committee of the School of Psychology at the University of Padova.

Motivational Simon task

The experiment was run using the E-Prime 2 software (Psychology Software Tools, Pittsburgh, PA) installed on a personal computer equipped with a 17" monitor. The structure of the experimental task respected the traditional Simon paradigm: the stimuli consisted of circles and squares presented randomly to the right or left of a central fixation point and displayed in two possible colours, red or green, against a white background. The participants responded to the colour of the stimuli by pressing one of two horizontally aligned response buttons on a keyboard (A for green and L for red Figures), using their left and right index fingers. Each trial started with the presentation of a central fixation cross for a random duration (200–500 ms), followed by the stimulus, which was presented for 250 ms.

The session started with a practise block of 40 trials and a following training block of 120 trials. After these two initial blocks, in which no feedback was delivered, reward and punishment blocks followed that comprised 224 trials each, with one break after 123 trials. The presence of a short practise block was designed to introduce the task before the planned recording of mean reaction times (RTs) during the training block: the mean RTs were calculated for the C and NC trials, with the left and right responses calculated separately.

On the basis of the four means and standard deviations, four separate algorithms for each participant—for the C and NC trials and each response—were calculated to identify the fastest responses that should be rewarded in the reward block [$RT < \text{mean RT of the training block} - (0.75 \times SD)$] and the slowest responses that have to be punished in the punishment block [$RT > \text{mean RT training block} + (0.75 \times SD)$].

Table 1 Means and standard deviations for the demographic characteristics of the tested samples; the tests concern the comparison between the old subjects and PD patients

	Young ($N = 27$)	Old ($N = 15$)	PD patients ($N = 15$)	Test (df)	p value
Age (years)	24.7 \pm 3.4	68.1 \pm 9.6	71.8 \pm 8.7	$t_{(28)} = -1.07$	ns
Gender	8 M	4 M	6 M	$\chi^2_{(1)} = .60$	ns
Education (years)	17.1 \pm 1.3	8.1 \pm 3.5	8.4 \pm 3.04	$t_{(28)} = .223$	ns

With the use of these algorithms, fast correct responses received a virtual bonus (+€0.15) in the reward block; while in the punishment condition, slow correct responses and errors were penalised by a virtual loss (–€0.15).

Acoustic feedback was given for errors in both conditions; however, errors were not penalised in the reward condition, whereas errors like slow responses were punished (–€0.15) in the punishment condition. After each feedback, the updated virtual budget that was collected appeared at the bottom of the screen; at the end of the experiment, each participant received information about their total virtual budget, as total amounts won and lost. The order of the reward and punishment blocks was counterbalanced across the participants.

Data analysis

The mean correct RTs and accuracy rates were calculated separately within every group for each experimental block—reward and punishment. The RT and accuracy data from the two blocks were also submitted to a diffusion model analysis [35]. Assuming that information accumulates during two-choice decisions until a response boundary is reached and the motor response is initiated, the diffusion model decomposes the performance into extra-decisional processes—perceptual and motor—and decisional processes. In this study, the diffusion model was adopted to obtain four parameters of interest: two decisional and two extra-decisional parameters.

The model parameter a , known as the response boundary, captures the distance between the response thresholds and is interpreted as a measure of conservatism. This parameter is a measure of response caution or speed–accuracy trade-off: with a larger response boundary, it takes longer for the decision process to reach its threshold, which decreases the probability of an erroneous response [40]. The second decisional parameter is represented by the starting point (z), which can map the a priori biases in the decision thresholds. Since the z parameter can only be interpreted in its relation to the a parameter, we calculated the relative starting point ($zr = z/a$), because if z differs from $a/2$ (i.e., $zr \neq 0.5$), then different amounts of information are required before deciding on option A or B [41].

As extra-decisional parameters, we considered the parameter v , i.e., the drift rate, to evaluate the relative amount of information per time unit that is needed, as well as the parameter $t0$, which consists of both the motor and encoding processes that precede the decisional phase and indicates the duration of all extra-decisional processes [42]. We employed the fast dm method to obtain these four values [43, 44]: in detail, we allowed the $t0$, z , v , and

a parameters to vary with each of the two trial conditions (C and NC trials) and estimated separate diffusion models for the reward and punishment blocks, for each participant in the three groups.

As the index of fit between the empirical and predicted cumulative RT distributions, the fast dm method [43, 44] was used to calculate a Kolmogorov–Smirnov (KS) test for each model, for which a significant result on the KS test ($p < .05$) signals model misfit. We performed tests of fit separately for each diffusion model (i.e., for each participant and for each experimental block, resulting in a total of 114 models) and only obtained a significant result for one young participant; therefore, the results presented here consider 26 young participants, 15 old participants, and 15 PD patients.

The mean correct RTs, accuracy rates, and each parameter of the diffusion model were separately analysed with a $2 \times 2 \times 3$ mixed ANOVA, including the within-subject factors block (reward vs punishment) and correspondence (C vs NC), as well as the between-subject factor group (young, old, and patients). A Bonferroni correction for multiple comparisons was applied for post hoc analysis.

Results

The performances of the three groups on the motivational Simon tasks are reported in Table 2, which provides the means, standard deviations, and confidence intervals for each group and each experimental condition's correct RTs and accuracy rates.

Reaction times

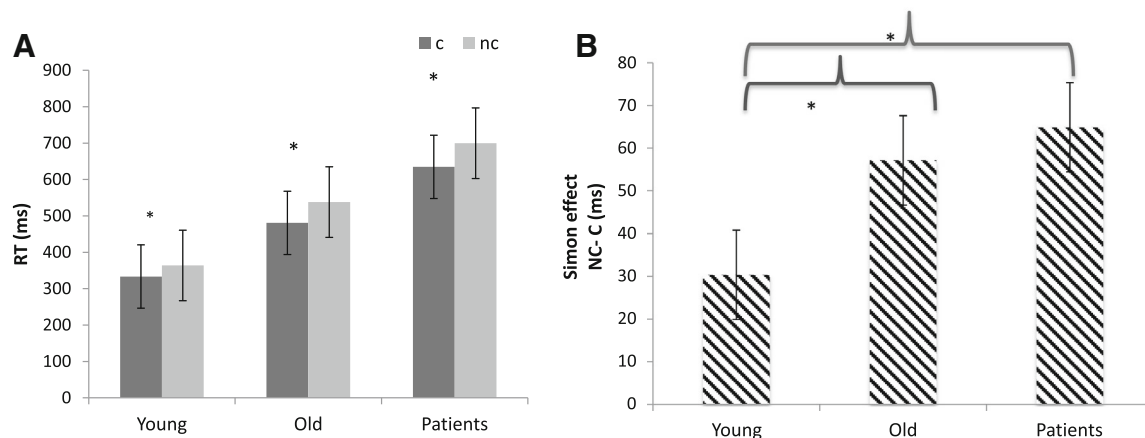
The rANOVA for correct RTs yielded a main effect of correspondence [$F(1, 54) = 258.45$; $p < .001$; $\eta_p^2 = .827$], confirming the presence of a significant Simon effect. The main effect of group [$F(2, 54) = 55.44$; $p < .001$; $\eta_p^2 = .67$] indicated a significant slowing of RT going from young to old and then to PD patients. The significant group \times correspondence interaction [$F(2, 54) = 13.08$; $p < .001$; $\eta_p^2 = .32$] was explored with a post hoc rANOVA on the Simon effect. The results of this additional analysis revealed that young participants showed a smaller Simon effect with respect to the older participants (30.35 vs 57.13 ms; 95 % CI –45.05, –8.51; $p < .005$) and the patients group (30.35 vs 64.88 ms; 95 % CI –52.79, –16.25; $p < .001$). Non-significant differences were found between the old and PD patients (Fig. 1). The interaction between block and correspondence was not significant [$F(2, 54) = 3.8$; $p = .056$; $\eta_p^2 = .06$].

Table 2 Means, standard deviations, and confidence intervals (95 %) of correct RTs and accuracy rates

Group	Block	Trial	Mean \pm SD RT (ms)	Confidence interval 95 % (RT; ms)		Mean \pm SD accuracy (%)	Confidence interval 95 % (accuracy; %)	
Young	R	C	324.1 \pm 45	287.9	360.4	92 \pm 5	90	95
		NC	358.7 \pm 42	322.9	394.5	82 \pm 11	78	86
	P	C	342.7 \pm 42	303.1	382.3	95 \pm 3	93	97
		NC	368.8 \pm 42	329.1	408.5	91 \pm 4	88	94
Old	R	C	483.3 \pm 90	434.7	531.9	96 \pm 2	94	99
		NC	545.6 \pm 89	497.6	593.5	86 \pm 7	81	91
	P	C	478.4 \pm 69	425.2	531.5	96 \pm 3	94	99
		NC	530.3 \pm 77	477.1	583.6	89 \pm 6	86	93
PD patients	R	C	628.6 \pm 148	580	677.2	91 \pm 7	89	94
		NC	694.3 \pm 148	646.3	742.3	86 \pm 10	81	91
	P	C	640.9 \pm 180	587.8	694.1	92 \pm 9	89	95
		NC	704.9 \pm 178	651.7	758.2	86 \pm 12	82	89

Simon effect (NC–C)

R reward block, P punishment block, C corresponding trial, NC non-corresponding trial

**Fig. 1** **a** RTs of correct responses in the C and NC trials. **b** Simon effect measured by RT. C corresponding trials, NC non-corresponding trials. Asterisks a significant difference refers to a p value $<.05$. The error bars represent standard errors

Accuracy rates

The rANOVA for accuracy rates yielded significant main effects for correspondence [$F(1, 54) = 73.42$; $p < .001$; $n_p^2 = .57$], block [$F(1, 54) = 10.94$; $p < .005$; $n_p^2 = .17$], and the following significant interactions: block \times correspondence [$F(1, 54) = 10.13$; $p < .005$; $n_p^2 = .16$] and block \times group [$F(2, 54) = 5.99$; $p < .005$; $n_p^2 = .18$]. Post hoc comparisons revealed an overall increased accuracy in NC trials of the punishment block; furthermore, only the young group showed a significantly higher accuracy level in the punishment condition ($p < .05$; see Fig. 3).

The significant three-way interaction of block \times correspondence \times group [$F(2, 54) = 5.61$; $p < .05$;

$n_p^2 = .17$] was explored with a mixed ANOVA on the Simon effect, with the factors block and group. The post hoc comparisons conducted to explore the significant interaction block \times group [$F(2, 54) = 7.83$; $p < .005$; $n_p^2 = .26$] yielded by this additional ANOVA showed that the magnitude of Simon effect was significantly different in the two blocks among the young group, with a greater Simon effect in the reward block (.10) compared to the punishment block (.045) ($p < .001$; 95 % CI .03, .082; $p < .001$); interestingly, this similar trend did not reach significance in old subjects ($p = .057$) and the difference between the Simon effect of the reward and the punishment blocks was not significant in PD patients (see Fig. 2).

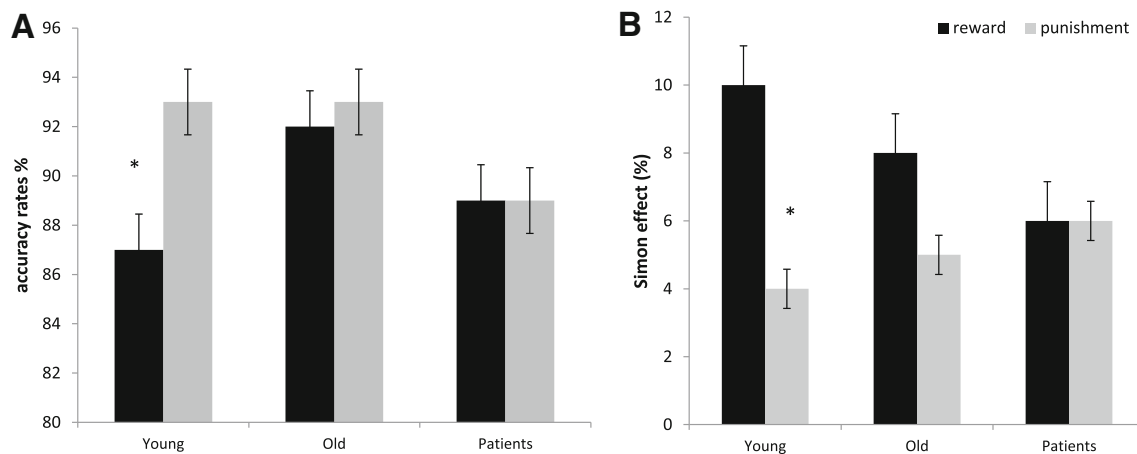


Fig. 2 **a** Accuracy rates in the two blocks. **b** Simon effect in the two blocks. Asterisks a significant difference refers to a p value $< .05$. The error bars represent standard errors

Boundary separation (a)

A significant effect of correspondence [$F(1, 53) = 36.4$; $p < .001$; $\eta_p^2 = .40$] showed that the overall decision process took longer to reach the threshold in the C trials. The main effect of group [$F(2, 53) = 20.4$; $p < .001$; $\eta_p^2 = .43$] indicated differences in the a values between the young and old subjects (.90 vs 1.11; 95 % CI $-.37, -.05$; $p < .01$), and between the old subjects and PD patients (1.11 vs 1.3; 95 % CI $-.37, -.01$; $p < .05$).

The significant block \times group interaction [$F(2, 53) = 8.02$; $p < .005$; $\eta_p^2 = .23$] showed a different block modulation of the a parameter in the three groups. The post hoc comparisons revealed that boundary separation, i.e., the a parameter, in the young participants increased in the punishment block, compared to the reward block (.96 vs .85; 95 % CI .033, .182; $p < .01$). An opposite pattern was found in the old group (Fig. 3a), in which the a parameter increased in the reward block with respect to the punishment one (1.17 vs 1.06; 95 % CI .015, .221; $p < .05$). No differences were found in the PD patients, who showed an absence of modulation in the a parameter by block.

The significant block \times correspondence \times group interaction [$F(2, 53) = 3.19$; $p < .05$; $\eta_p^2 = .10$] and post hoc comparisons revealed that the block-dependent modulation of the a parameter found in young and old groups was driven by responses to the C trials. In the C trials of the punishment block, the young adults showed higher boundary separation, in comparison to the C trials of the reward block (1.06 vs .88; 95 % CI .068, .280; $p < .005$); conversely, older adults showed lower boundary separation in the punishment block, compared to C trials of the reward block (1.13 vs 1.28; 95 % CI .011, .29; $p < .05$).

Response bias (z/a)

The main effect of block [$F(1,53) = 34.15$; $p < .001$; $\eta_p^2 = .39$] and the block \times group interaction [$F(2, 53) = 19.14$; $p < .001$; $\eta_p^2 = .41$] showed that older adults were highly biased in favour of the correct response in the punishment block, with respect to the young group (.96 vs .66; 95 % CI .16, .45) and the PD patients (.96 vs .53; 95 % CI .26, .59) (Fig. 3b).

In addition, the main effect of group [$F(2, 53) = 14.21$; $p < .001$; $\eta_p^2 = .34$] revealed that while the response bias values were significantly higher in older adults compared to young adults (.74 vs .61, 95 % CI .04, .12; $p < .005$), PD patients showed significantly lower values with respect to the old group (.53 vs .61; 95 % CI $-.31, -.11$; $p < .001$).

Non-decision time (t_0)

The main effect of group [$F(2, 53) = 8.19$; $p < .005$; $\eta_p^2 = .23$] showed that the mean non-decision time was significantly higher for the PD patients, with respect to the young (.60 vs .27; 95 % CI .13, .54; $p < .005$) and older adults (.60 vs .37; 95 % CI .001, .46; $p < .05$).

Drift rate (v)

A significant effect of block [$F(2, 53) = 9.76$; $p < .005$; $\eta_p^2 = .15$] indicated that the overall drift rate values were higher in the punishment block compared to the reward one. The main effect of correspondence [$F(1, 53) = 26.25$; $p < .001$; $\eta_p^2 = .33$] showed that the drift rate was lower for the non-corresponding than for the corresponding trials. Finally, the main effect of group [$F(2, 53) = 22.75$; $p < .001$; $\eta_p^2 = .46$] and the following post hoc comparison

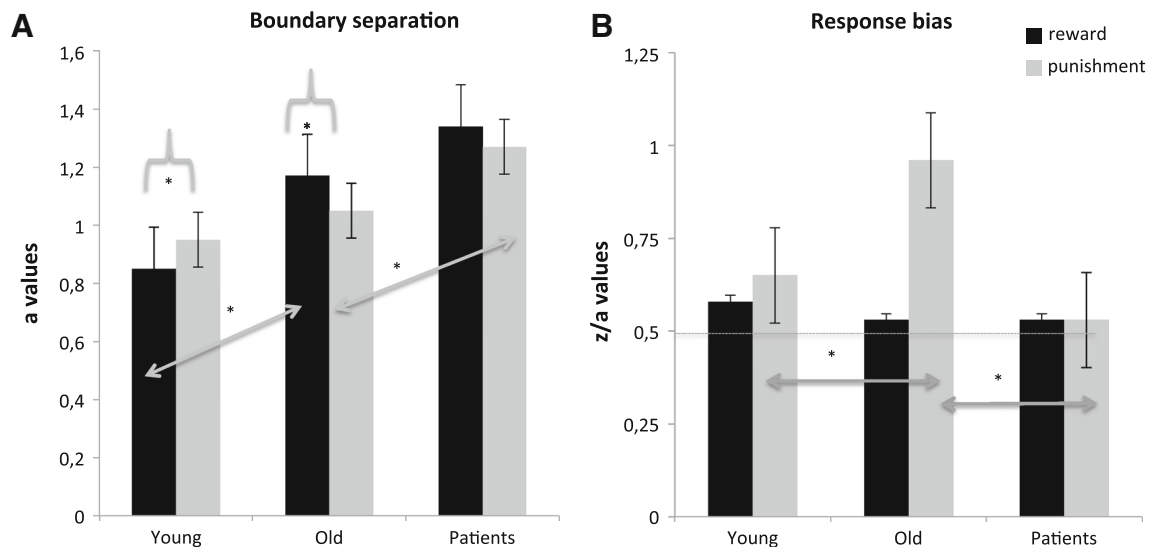


Fig. 3 Decisional parameters of the diffusion model. **a** Boundary separation. **b** Response bias (z/a): values above the line indicate a bias for correct response. Asterisks a significant difference refers to a p value $<.05$. The error bars represent standard errors

revealed that the PD patients showed significantly lower drift rate values, with respect to the young (2.34 vs 4.02; 95 % CI $-2.3, -1.06$; $p < .001$) and older adults (2.34 vs 3.48; 95 % CI $-1.8, -.44$; $p < .005$).

Discussion

In the present study, we explored how the interaction between motivation and cognitive control changes in a condition of physiological decline in dopaminergic functionality, i.e., healthy ageing, and in a condition of dopaminergic dysregulation, i.e., PD patients under dopaminergic treatment. To do so, a new paradigm called the motivational Simon task was designed with the aim of measuring cognitive control in different motivational contexts.

Virtual reward and virtual punishments were introduced in a Simon task [4], based on the previous literature employing them as motivational incentives to motivate the participants towards fast and accurate responses in a cognitive task [8, 13, 18–21]. The effects of these two types of virtual feedback on the perceptual and executive stages of performance were explored using diffusion model analysis [35], which permits the separate study of the motor and non-motor components of a performance; for this reason, it appeared to be the most appropriate method of studying ageing and PD.

Firstly, our results show that motivational incentives, like rewards and punishments, modulate the executive stages of information processing differently. Interestingly, this finding highlights the fact that even virtual rewards and

punishments can act as effective motivational incentives and can successfully induce different motivational contexts that may significantly modulate performance in a conflict task.

In addition, our data show that this capacity is preserved in healthy ageing. Older adults show a preserved capacity to manage their cognitive resources in response to different motivational conditions, even if implementing a different approach to the task, respect to the young subjects. Older adults show a greater speed–accuracy trade-off in the reward condition, while the young subjects manifest the opposite pattern, with bigger speed–accuracy trade-off in the punishment condition.

This different response pattern is compatible with the well-known age-related differences in speed–accuracy balancing and decision-making: while younger adults generally perform quickly and are more accepting of errors, the elderly respond slowly in order to try being more accurate [45–49]. Interestingly, the presence of opposite patterns in young and elderly participants is in line with the literature about the “age-related positivity effect” [50–55]: even in our study, the elderly participants focussed more strongly and tended to perform better when positive information, rather than negative, was available.

Despite these significant differences, it is important to highlight that the capacity to modulate the executive components of performance in response to different motivational incentives is preserved in healthy ageing. Speculatively, elderly participants are still able to modulate their performance in relation to different motivational incentives because the striatal reward signals, i.e., the activity of the dopaminergic network involving the ventral

striatum, are preserved and permit efficient valence processing, at least in simple tasks like our motivational Simon task [26]. Our results concerning medicated PD patients seem to be in line with this assumption: in the present study, the medicated PD patients showed an altered capacity to modulate their performance depending on the motivational incentives.

With respect to a control condition represented by matched healthy subjects, the medicated PD patients did not adapt their performance in response to positive or negative feedback and showed comparable responses in two different motivational contexts. This pattern of performance could be explained in light of the dopaminergic overdose hypothesis [34, 56–58]: DRT may overstimulate the ventral fronto-striatal system, blocking the physiological dopamine dips induced by negative feedback, the processing of which would be impaired [59, 60].

The altered functionality of the dopaminergic reward system has been suggested to cause the significant feedback processing and decision-making impairment that have been increasingly documented in medicated PD patients [60–66]. Following this hypothesis, a dopaminergic overdose in the ventral dopaminergic system would compromise valence processing, which in turn would result in a compromised interaction between motivation and cognitive control.

Taken together, our findings support the hypothesis that the interaction between motivation and cognitive control may be mediated by the cerebral level of DA [32], in line also with recent evidence that highlighted the role of midbrain dopaminergic projections in the integration of motivation and cognitive processes [67].

Furthermore, we suggest focussing attention on the ventromedial dopaminergic system, the preservation of which in healthy ageing and impairment in medicated PD patients may explain the different impacts of ageing and PD on the interaction between motivation and cognitive control. Finally, one important implication of the present study concerns the clinical context of neuropsychological rehabilitation, in light of the fact that most rehabilitation procedures in clinical practice are based on feedback-guided learning. Our results not only provide evidence that different motivational contexts can be induced by virtual feedback, but also show a possible fallacy of feedback-based learning procedures with clinical samples like PD patients or patients in general with impaired feedback processing.

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Conflict of interest On behalf of all of the authors, the corresponding author states that there are no conflicts of interest.

Ethical standard The study protocol was in accordance with the Helsinki Declaration on human rights and was approved by the Ethics Committee at the School of Psychology, University of Padova.

Informed consent All participants signed an informed consent form prior to their inclusion in the study.

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