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Elderly adults show higher ventral striatal activation in response to motor performance related rewards than young adults

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Abstract

Feedback on motor performance activates the striatum and boosting ventral striatum activation with rewarding feedback during motor training supports the consolidation of the learned skill. Aging is associated with changes of the reward system, including striatal and extrastriatal loss of dopamine receptors. How these changes interact with the blood oxygenation level dependent (BOLD) response is, however, not yet fully understood. While it is known that reward prediction and reward-based decision-making differ between young and elderly healthy adults, the influence of age on the processing of rewarding feedback on motor performance have not been investigated so far.

Nineteen young (26.42±2.84 years) and 18 elderly (65.39±6.40 years) healthy adults performed an arc-tracking task including performance feedback linked to a monetary reward after half of the trials, while undergoing functional magnetic resonance imaging (fMRI). The BOLD effect was compared in three predefined regions of interest: Ventral and dorsal striatum plus primary motor cortex.

Our study demonstrates differences in the processing of motor performance related reward between young and elderly healthy adults. While both groups earned similar amounts of money linked to their own performance, the ventral striatal response to the rewarding feedback was higher in the older group. Deficient prediction about the rewarding feedback, a higher motivational status or compensation for a reduced number of dopamine receptors in the elderly might be possible explanations. How this interacts with the reward-induced improvement of motor skill consolidation, as observed in young subjects, has to be clarified.

Highlights

- Processing of rewarding feedback changes throughout adulthood
- Elderly show higher ventral striatal response to reward linked to motor performance
- Deficient reward prediction, higher motivation or compensation for a reduced number of dopamine receptors in the elderly might be possible explanations

Keywords

Reward processing, performance feedback, motor tracking, fMRI, aging, striatum

Abbreviations

BOLD	blood oxygenation level dependent
CHF	Swiss Francs
DA	dopamine
dStr	dorsal striatum
fMRI	functional magnetic resonance imaging
IMI	intrinsic motivation inventory
M1	primary motor cortex
ROI	region of interest
vStr	ventral striatum

Introduction

The receipt of a reward is associated with increased striatum activation [11, 21]. More specifically, intrinsic reward (e.g., performance feedback) leads to increased activation of the ventral striatum (vStr), which even further increases when feedback is linked to an extrinsic reward (e.g., money). Notably, in a rewarded task the neural activity in the striatum correlates with striatal dopamine (DA) release [16]. Moreover, studies performed with healthy young individuals demonstrated that training under a rewarded condition positively influences motor skill learning when compared with a control condition [21]. However, it must be considered that the human reward system changes with age, including striatal and extrastriatal loss of DA-receptors [9, 13]. Previous research has revealed differences in reward prediction [5, 17] and reward-based decision-making [4] between young and elderly healthy adults. These studies found a decreased striatal response to reward, reward prediction errors, and reward anticipation in elderly. Interestingly, when using tasks which did not require learning, striatal activity was not different [15]. Yet, it is unclear how these changes over the lifespan affect reward processing that is related to the performance in a motor task. Considering the loss of DA receptors, adequate feedback-related motor learning might actually require an upregulation of the neural response to rewarding feedback in an aging population. A potentially reduced activation, on the other hand, could be an implication for impaired motor performance, as it has been observed in some cognitive and motor tasks [20], and thereby negatively affect the motor system’s ability to adapt to changing situations.

We therefore asked whether processing of motor performance related reward differs between young and elderly healthy adults. For this purpose, we had 20 young and 20 elderly healthy subjects perform a motor skill task while undergoing functional magnetic resonance imaging (fMRI). An arc-tracking task was used, and a performance feedback including a monetary reward linked to performance was given after half of the trials. The striatal response to the rewarding feedback was then compared between the two groups.

Methods

Participants

Twenty young (22 - 35 years of age) and 20 elderly (over 55 years of age) healthy native German-speaking adults participated in this study which was approved by the competent ethics committee (EKNZ BASEC 2016-00079). All subjects gave written informed consent according to the Declaration of Helsinki. Exclusion criteria included psychiatric disorders, intake of central nervous drugs (e.g. antidepressants), and pregnancy (tested for each woman of child-bearing age). Moreover, an MRI-safety-questionnaire was used to check for any MRI contraindications. All subjects were naïve to the task, received identical instructions and underwent identical study procedure. They received financial compensation depending on their performance during the motor task.

Procedure

The study required one measurement session at the cereneo, center for neurology and rehabilitation in Vitznau, Switzerland. After the informed consent procedure, subjects were asked to fill in a depression- (Beck Depression Inventory, BDI II, Beck, et al. [1]) and a handedness-questionnaire (Edinburgh Handedness, Williams [22]). Additionally, cognitive screening was performed using the Montreal Cognitive Assessment (MoCA, Nasreddine, et al. [12]). Finally, after completion of the fMRI task, subjects were asked to fill in a motivation assessment (Intrinsic Motivation Inventory, IMI, http://selfdeterminationtheory.org/intrinsic-motivation-inventory).

Motor task

To examine the processing of motor performance related reward, both groups performed a modified arc-pointing task [18, 21], which allowed to gain money linked to motor performance while undergoing fMRI. A spherical reflective marker was attached to the index finger of the dominant hand. This marker was continuously tracked using a MRI-compatible motion capture system (Oqus MRI, Qualysis AB, Gothenburg, Sweden) and was synchronized with a representative cursor on the screen by a computer program written in “Presentation 16.3” software (Neurobehavioral Systems, Inc., Albany, NY, USA). Hence, by moving the wrist of the dominant hand subjects could steer a cursor through a semicircular channel in clockwise direction and in their preferred movement speed from a defined start- to an end-box while trying not to leave the channel. For a more detailed description of the setup see Widmer, et al. [21].

The assessment started with a short familiarization period of 20 trials. This was used to adapt the size of the channel in order to make sure that all participants are able to perform the rewarded task at a similar performance level and, since monetary rewards were linked to performance, to balance out amounts of money gained in the two groups. Difficulty was adjusted by changing the channel width, which was set 12 pixels (≈0.12º visual angle) smaller after trials with more than 70% of the trajectory inside the channel, and 12 pixels wider when less than 30% of the trajectory were within the channel. Minimal channel size was 12 pixels.

Thereafter, each subject performed four blocks of 25 trials with a fixed channel size (as evaluated during the familiarization period) while undergoing fMRI. Subjects were shown a feedback screen including the trajectory travelled by the cursor and a monetary reward linked to their performance after 50% of the trials (Figure 1 (a)), or a neutral stimulus after the other half of the trials (Figure 1 (b)). They were unaware, however, that they were only rewarded when the performance of the current trial was better than the median of the preceding ten trials. Performance was defined as the ratio of data points lying within the channel, which was directly linked to a monetary reward in Swiss Francs (CHF). That is, if, for example, 80% of the trajectory lay within the channel (and this was better than the median of the preceding ten trials), the subject won 80 Rappen (=0.80 CHF, ≈0.8 $). Visual stimuli were presented on a screen (0.64 x 0.4 meters; 1920 x 1200 pixels) placed behind the scanner, visible to the participant via a mirror attached to the coil above their head (distance screen - mirror ≈1.90 meters).

[Figure 1]

Figure 1: ***Trial sequence****. After placing the cursor in the start box, the box eventually turned green ("ok-to-go" signal) and subjects were free to start the movement whenever ready. The placing of the cursor in the start box, as well as the period from "ok-to-go" to the actual start of the movement were self-paced and hence of variable length (var), as was the movement time (MT) to steer the cursor through the semicircular channel. As soon as the target box was reached, the screen froze.* ***(a) Feedback screen*** *presented after feedback trials (FB TRIAL), that is, if performance of the current trial (P_t) was better than the median ($\tilde{P}$) over the previous ten trials $\{P_{t-1}, P_{t-2}, \ldots P_{t-10}\}$. The money gained in the current trial (in German: "In diesem Versuch gewonnen: 0.7 CHF") and the total money won ("Total: 0.7 CHF"), both in Swiss Francs (CHF), were presented together with the trajectory travelled by the cursor.* ***(b) No-feedback trial.*** *If P_t was not better than $\tilde{P}$, subjects were shown a neutral visual control stimulus (NO-FB TRIAL). Note that the amount of money gained in the current trial as well as the total money were replaced by three question marks and the trajectory was omitted.*

Either way, the next trial began after a delay period (break). Notably, onsets and durations of six of the seven regressors (reg.) are marked on the time axis (TOP). The 7^{th} regressor was a parametric modulation of the feedback regressor by the magnitude of the monetary reward.

Behavioral data analysis

Ratios of data points lying within the arc-channel and movement durations were averaged over 25 consecutive trials, resulting in four blocks. Two repeated measures ANOVA with "block" as within-subject factor (levels: 1, 2, 3 and 4) and the age "group" (levels: elderly and young) as between-subject factor were then calculated in SPSS (SPSS, version 23, IBM Corp., Armonk, NY, USA). Degrees of freedom were corrected for non-sphericity using the Greenhouse-Geisser correction where the assumption of sphericity was violated according to the Mauchly's test. In addition, an unpaired two-sample *t*-test was used for the between-group comparison of the average amount of money won per rewarded trial. Questionnaires were compared using the Mann-Whitney *U* test. A two-tailed value of $p<0.05$ was considered significant.

fMRI data acquisition and analysis

fMRI data acquisition was performed using a Philips Ingenia 3.0T MRI scanner (Philips Healthcare, Best, The Netherlands) equipped with a 32-channel dS head coil. Before fMRI, anatomical images of the entire brain were obtained using a T1-weighted three-dimensional magnetization-prepared rapid gradient-echo (MPRAGE) sequence (170 slices, TR=6.8 ms, TE=3.1 ms, flip angle=8°, FOV=256 mm x 240 mm x 204 mm, matrix size=256 x 240, voxel size=1.00 mm x 1.00 mm x 1.20 mm). Subsequent fMRI data was acquired using a sensitivity encoded (SENSE, factor 1.8) single-shot echo planar imaging technique (FEEPI; TR=2.35 s; TE=32 ms; FOV=240 mm x 240 mm x 140 mm; flip angle=82°; matrix size=80 x 80; voxel size=3 mm x 3 mm x 3.5 mm). To establish a steady state in T1 relaxation, three dummy scans preceded data acquisition of each block. Moreover, cardiac and respiratory cycles were continuously recorded (Invivo Essential MRI Patient Monitor, Invivo Corporation, Orlando, FL, USA) to allow correction of fMRI data for physiological noise.

fMRI data were analyzed using Matlab R2014a and the SPM12 software package (Statistical Parametric Mapping, Institute of Neurology, London, UK; http://www.fil.ion.ucl.ac.uk/sp). All functional images were realigned to the first volume of the fMRI session. The anatomical image was co-registered to the mean functional image, and then segmented and normalized to the standard stereotactic space defined by the Montreal Neurological Institute. Subsequently, normalization parameters were applied to all functional images, which were resliced to 3mm x 3mm x 3mm voxels, and then smoothed using an 8mm full-width-at-half-maximum Gaussian kernel.

For first level analysis, a general linear model (GLM) was specified for each subject by defining seven recurring regressors (Figure 1). To do so, corresponding onsets and durations were extracted from Presentation-log-files using custom Matlab routines. Moreover, correction for physiological noise was performed via RETROICOR [6, 8] using Fourier expansions of different order for the estimated phases of cardiac pulsation (3rd order), respiration (4th order) and cardio-respiratory interactions (1st order) [7]. The corresponding confound regressors were created using the Matlab physIO Toolbox (Kasper, et al. [10], open source code available as part of the TAPAS software collection: http://www.translationalneuromodeling.org/tapas/).

To separate the signal change induced by the informative content of feedback from irrelevant visual information, the relative signal change elicited by rewarding feedback in contrast to the visual control stimulus ("FB vs noFB" contrast), both compared to baseline activation during waiting periods, was calculated and represented as β-values. These were then averaged over different regions of interest (ROI), using an in-house Matlab routine, resulting in an average effect size per ROI for each subject. Partition of the striatum in vStr and dorsal striatum (dStr) was performed according to Lutz, et al. [11], and specifically selected due to previous work, which demonstrated a main role of the vStr in the reward-driven optimization of motor skill learning [21]. In addition, M1 was included as feedback concerned performance in a motor task.

The resulting effect sizes per ROI were then statistically compared using SPSS. To test for significant activations, we performed one-sample *t*-tests against the null hypothesis of zero activation. A repeated measures ANOVA with "ROI" as within-subject factor (levels: vStr, dStr and M1) and age "group" (levels: elderly and young) as between-subject factor was applied. Again, we corrected degrees of freedom for non-sphericity if this assumption was violated. Significance was defined by a p-value smaller than 0.05. Post-hoc *t*-tests were performed where significant main effects or interactions were found.

Results

One subject of each age group was identified as outlier (*β*-value of at least one ROI < *mean* – 2 x *SD* or > *mean* + 2 x *SD*) and was therefore excluded from further analysis. In addition, one elderly subject had to be excluded due to intake of central nervous drugs (antidepressants), hence resulting in a final sample of 37 participants. BDI II and MoCA values of both groups were clinically unobtrusive (Table 1 A)).

A) Subject characteristics		
	Young	Elderly
N (dropouts)	19 (1)	18 (2)
Age (mean±SD)	26.42±2.84	65.39±6.40
Sex (female)	10	6
Handedness (right / left / bi-manual)	17/ 1/ 1	15/ 0/ 3
BDI II (mean±SD) ∗	1.26±2.64	1.78±1.93
MoCA (mean±SD)	28.53±0.77	27.39±2.09

B) Intrinsic Motivation Inventory (IMI)		
Interest / enjoyment ∗	4.83±0.75	5.81±1.09
Perceived competence	4.25±0.72	4.67±0.94
Effort	5.45±0.87	5.51±0.98
IMI total	4.84±0.56	5.33±0.66
Subjective valuation of monetary reward	3.57±1.49	2.83±1.24

Table 1: ***A)*** *N is the number of subjects per group, SD is standard deviation and age is reported in years. Questionnaires (range, best score): BDI II, Beck Depression Inventory II (0-63, 0); MoCA, Montreal Cognitive Assessment (0-30, 30).*

B) *Results from Intrinsic Motivation Inventory (IMI, 7-point Likert scale), presented as mean±SD. Note: The IMI was filled by 18 young and 9 elderly participants.*

∗ Significant difference between groups (p<0.05).

Behavioral

Repeated measures ANOVA revealed no learning effects, i.e. no effect of the four blocks (à 25 trials) on performance ($F_{1.74,\ 60.78}$=1.36, p=0.26) and no “Block*Group” interaction ($F_{1.74,\ 60.78}$=0.06, p=0.92). However, the younger group performed significantly better than the elderly ($F_{1,\ 35}$=4.77, p=0.036). Still, young and elderly subjects earned, on average, similar amounts of money per feedback-trial (0.69±0.10 CHF vs. 0.63±0.11 CHF; t_{35}=1.63, p=0.112). Thereby, the average duration of the self-paced movement did not change over blocks ($F_{1.45,\ 50.65}$=0.97, p=0.36) and was not influenced by the age group (main effect “Group”: $F_{1,\ 35}$=2.68, p=0.111; “Block*Group” interaction: $F_{1.45,\ 50.65}$=2.37, p=0.118).

Imaging

For the “FB vs noFB” contrast, both groups showed significant activations of all ROIs included in the analysis (Figure 2, all p<0.05). ANOVA revealed that β-values differed between ROIs ($F_{2,\ 70}$=16.39, p<0.001) and a significant “ROI*Group” interaction was observed ($F_{2,\ 70}$=3.62, p=0.032). Post-hoc t-tests (two-tailed, uncorrected) uncovered a higher activation of the vStr for the elderlies ($t_{31.00}$=2.05, p=0.048), while dStr and M1 activations were similar (t_{35}=0.94, p=0.354 and t_{35}=-0.04, p=0.966, respectively). By looking at the “FB vs noFB” contrast, as described earlier, we chose to first separate the signal change induced by the informative content of rewarding feedback from irrelevant visual input on voxel level (see Methods). Responses to visual control stimuli, however, were similar between groups (main effect “Group”: $F_{1,\ 35}$=0.00, p=0.994; “ROI*Group” interaction: $F_{2,\ 70}$=0.60, p=0.554), indicating that the observed difference was mainly driven by differential responses to the rewarding feedback.

Finally, over the whole study population (independent from the age group), the signal in the striatum was influenced by the amount of money gained in a specific trial (vStr: t_{36}=2.92, p=0.003, and dStr: t_{36}=2.45, p=0.010). The groups, however, did not differ in their striatal response to this parametric modulation of the feedback regressor by amount of money (main effect “Group”: $F_{1,\ 35}$=0.03, p=0.960; “ROI*Group” interaction: $F_{1,\ 35}$=0.16, p=0.688).

[Figure 2]

Figure 2: *BOLD effect to the "FB vs noFB" contrast expressed as β-values in ventral (vStr, blue) and dorsal striatal (dStr, red) regions of interest (ROIs), as well as in primary motor cortex (M1). N=37. Mean and standard error (SE).*

Motivation

All young (*N*=18) and a subset of the elderly subjects (*N*=9) filled the "interest/enjoyment", "perceived competence" and "effort" subscales of the IMI, plus provided a subjective valuation of the monetary rewards linked to their performance (Table 1 B)). Elderlies reported higher "interest/enjoyment" (*U*=35.5, *p*=0.012), but groups did not differ in the other subscales.

Discussion

Here, using fMRI, we investigated whether the neural processing of a monetary reward, whose magnitude depended on individual performance in a motor task, differs between young and elderly healthy adults. To our best knowledge, this is the first study showing increased activation in response to rewarding motor performance feedback in an elderly population. The vStr, a key region of reward processing that has been shown to mediate reward-related motor learning [21], was more strongly activated in the elderly.

Our findings are in contrast with previous research, which has revealed decreased striatal response to reward, reward prediction errors, and reward anticipation in elderly when compared to young healthy adults [4, 5]. However, Samanez-Larkin, et al. [15] compared the frontostriatal representation of reward between younger and older adults in two different tasks that either did or did not depend on probabilistic learning. They observed reductions in the frontostriatal representation of prediction errors during probabilistic learning in older adults. However, they also reported evidence for stability across adulthood in the representation of reward outcome in a task that did not require learning. This is in line with Schott, et al. [17], who found significantly higher activation of the vStr during reward anticipation (reward cues vs. neutral cues) in a group of young relative to healthy elderly subjects, but similar to our findings, a reverse pattern with even increased vStr activation in the elderly during reward outcome (positive feedback versus neutral feedback). Although reward magnitude was not announced before reward presentation in our task, attentively steering a cursor along the arc-channel under visual control may have enabled subjects to evaluate their performance online and thus to make predictions about the feedback. Hence, even if striatal activation was not different (p=0.42) for the period preceding reward presentation (Figure 1: 4^{th} reg.), deficient reward prediction in the elderly might be a plausible explanation for the higher vStr activation as observed in our study. Since older adults are less capable of learning from prediction errors [15], it could be speculated that they are also possibly less capable of adjusting predictions.

In our previous experiments, it was consistently the vStr rather than the dStr that was more strongly activated by monetary reward after good motor performance [12, 22]. It might thus well be that, as an epiphenomenon, we were more likely to find an age difference in the ROI showing the most robust response to such kind of reward. Alternatively, ventral and dorsal striatum have distinct functions (action-value learning vs. stimulus-value learning) [19]. Hence, it could be that action-value learning is more affected by age. In healthy young, increasing ventral striatal activation in response to performance feedback (e.g., by linking performance to a monetary reward) comes along with better overnight task consolidation [21]. However, considering that the amount of cortical DA-receptors decreases with age [9], elderlies may need higher striatal activations to experience a similar dopaminergic stimulation [3]. Dreher, et al. [3] demonstrated that elderly subjects with lower basal dopamine levels showed a greater reward-related BOLD activity in the prefrontal cortex, while an opposite pattern was observed in younger subjects. This compensatory mechanism may involve complex and interactive effects between the BOLD response and the reduction of dopamine receptors in the older subjects [3, 9, 13].

Moreover, in our experiment, the reward was linked to individual task performance and therefore possibly hinged on motivation. As the motivation to work for a reward relies on dopaminergic activity in nucleus accumbens [14], which drives vStr activation, the greater vStr response to the rewarding feedback could be explained by a higher motivational status of the older adults. Indeed, the elderly reported higher “interest / enjoyment” for performing our experiment. However, compared to younger adults they also reported similar subjective valuation of the money gained. Notably, only half of the elderly participants filled the IMI questionnaire and thus the sample size was small.

One limitation of this study is the vague definition of motor performance by the ratio of points lying inside the arc-channel, as the individual performance is influenced by the different channel sizes and the self-selection of movement speeds by the subjects. This does, hence, not allow us to test whether differential striatal activations coming with age have an influence on strictly defined motor skill learning. Furthermore, the resulting variability might be the reason why no significant learning could be shown in the present study. However, the manipulation of the channel size was intended to equalize the performance across subjects and the average duration of the movement did not differ between the groups. Moreover, even though the elderly performed somewhat worse and therefore earned, on average, CHF 0.06 less money per reward-trial (not significant), they still showed greater striatal activation in response to rewarding feedback compared to the young group. However, aging can affect the cerebrovascular system, which in turn could affect neurovascular coupling, the basis of the BOLD signal [2]. We tried to minimize this concern by studying only individuals who were healthy, were receiving no medications, and had no signs of pathology on structural MRI.

In summary, our study demonstrates differences in the processing of motor performance related reward between young and elderly healthy adults. While both groups earned similar amounts of money linked to their own performance in a motor task, the vStr response to the rewarding feedback was considerably higher in the elderlies. Deficient prediction of reward, higher motivational status or compensation for a reduced number of DA receptors might be possible explanations.

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Disclosures

The authors report no conflicts of interest in this work.

Author contributions

Experimental design: MW, ARL, KL.

Data collection: SS, MW.

Data analysis: SS, MW, KL.

Manuscript: SS, MW, ARL, KL.

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