DOI:
10.1016/j.bpsc.2021.05.009

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

Archival Report

Biological Psychiatry: CNNI

Ketamine Modulates the Neural Correlates of Reward Processing in Unmedicated Patients in Remission From Depression

Vasileia Kotoula, Argyris Stringaris, Nuria Mackes, Ndabezinhle Mazibuko, Peter C.T. Hawkins, Maura Furey, H. Valerie Curran, and Mitul A. Mehta

ABSTRACT

BACKGROUND: Ketamine as an antidepressant improves anhedonia as early as 2 hours after infusion. These drug effects are thought to be exerted via actions on reward-related brain areas—yet these actions remain largely unknown. Our study investigates ketamine's effects during the anticipation and receipt of an expected reward, after the psychotomimetic effects of ketamine have passed, when early antidepressant effects are reported.

METHODS: We examined ketamine's effects during the anticipation and receipt of expected rewards on predefined brain areas, namely, the dorsal and ventral striatum, ventral tegmental area, amygdala, and insula. We recruited 37 male and female participants with remitted depression who were free from symptoms and antidepressant treatments at the time of the scan. Participants were scanned 2 hours after drug administration in a double-blind crossover design (ketamine: 0.5 mg/kg and placebo) while performing a monetary reward task.

RESULTS: A significant main effect of ketamine was observed across all regions of interest during the anticipation and feedback phases of win and no-win trials. The drug effects were particularly prominent in the nucleus accumbens and putamen, which showed increased activation on the receipt of smaller rewards compared with neutral. The levels of (2*R*,6*R*)-hydroxynorketamine 2 hours after infusion significantly correlated with the activation observed in the ventral tegmental area for that contrast.

CONCLUSIONS: These findings demonstrate that ketamine can produce detectable changes in reward-related brain areas 2 hours after infusion, which occur without symptom changes and support the idea that ketamine might improve reward-related symptoms via modulation of response to feedback.

https://doi.org/10.1016/j.bpsc.2021.05.009

Major depressive disorder is characterized by altered reward processing and a reduced ability to modulate behavior as a function of rewards (1). Deficits in reward processing can precede the onset of depression (2), are linked to anhedonia, and persist during remission (3,4). Ketamine, an NMDA receptor antagonist, produces robust antidepressant effects that occur as early as 2 hours after drug infusion, peak at 24 hours, and last up to 1 week (5). In relation to reward processing, the drug improves anhedonia, a symptom known to be resistant to standard antidepressant treatment (6). To our knowledge, however, no study has examined whether ketamine's ability to improve anhedonia is the result of direct modulation of reward processing areas that is not secondary to changes in symptoms. In this study, we have used a well-validated functional magnetic resonance imaging (fMRI) task, the monetary incentive delay (MID) task (7), in order to examine whether the drug engages brain areas involved in reward processing 2 hours after its administration in a relatively large sample of treatment-free and symptom-free volunteers with remitted depression.

In the brain, reward processing is mainly subserved by regions that are part of the mesocorticolimbic pathway (8). Imaging studies that have used the MID task to examine reward processing in healthy volunteers showed that not only striatal regions, especially the caudate and the putamen, but also the insula and frontal brain areas are activated during the anticipation phase of the MID task when a monetary reward is expected (9). During the feedback phase of the task when the expected reward is delivered, a similar set of brain regions appear to be involved (10). Recent meta-analyses have shown that in depression, the ventral striatum, caudate, and putamen present with decreased activation during the anticipation and feedback phases of the MID (2,11–14). This hypoactivation of reward processing areas observed in depression also persists in remission, with studies indicating that compared with healthy control subjects, volunteers with remitted depression show blunted responses to reward (3) and decreased activation in prefrontal (4) and striatal (15) regions during loss anticipation and outcomes. Given the central role of reward processing in depression, compounds that target these areas are considered promising candidates for alleviating depression, including anhedonia (16).

SEE COMMENTARY ON PAGE 241

ISSN: 2451-9022 Biological Psychiatry: Cognitive Neuroscience and Neuroimaging March 2022; 7:285–292 www.sobp.org/BPCNNI

Ketamine improves anhedonia as early as 2 hours after a single infusion, although the neural basis of these effects is only beginning to be understood. Using ^{18}F-fluorodeoxyglucose positron emission tomography imaging at 2 hours after dosing, glucose metabolism in the dorsal anterior cingulate cortex and the putamen correlated with reduced anhedonia in patients with treatment-resistant bipolar depression (17). In patients with major depressive disorder, reductions in anhedonia correlated with increased glucose metabolism in the dorsal anterior cingulate cortex and hippocampus (18). Anhedonia is not a unitary construct, with separable components including reward anticipation and feedback or delivery (19) as measured by the MID. Research in nonhuman primates suggests that ketamine treatment could ameliorate blunted anticipatory responses to appetitive stimuli by normalizing brain activation in the subgenual anterior cingulate cortex (sgACC) (20). One study in patients with depression investigated ketamine-induced changes in brain activity and anhedonia using a reward-related fMRI task, demonstrating a reduction in sgACC hyperactivity to positive feedback in 14 patients tested within 5 days of a ketamine infusion (21). The fact that the changes in the metabolism and activation of reward-associated brain areas temporally overlap with symptom changes makes it difficult to determine whether these changes are due to the primary effects of the drug or are secondary to the effect of ketamine on depressive symptoms. While these positron emission tomography and fMRI studies provide insights into the neural mechanisms that accompany ketamine's early antidepressant action, the effects on brain regions associated with anticipatory and feedback components of reward tasks during the emergent period of the antidepressant response (2–24 hours) are not known.

At a neuronal level, ketamine and its main metabolite, norketamine, indirectly activate the postsynaptic AMPA receptors and trigger molecular pathways, including BDNF (brain-derived neurotrophic factor) and mTOR (mechanistic target of rapamycin) pathways that lead to an increase in synaptic plasticity, which has been linked to the antidepressant effects of the drug. [for review, see (22)]. Another metabolite, (2*R*,6*R*)-hydroxynorketamine [(2*R*,6*R*)-HNK], can bind and activate AMPA receptors directly and thus trigger the initiation of plasticity-related molecular processes (23). In animal models of anhedonia, changes in plasticity markers after administration of ketamine have been linked to increased activations of the reward pathways that are mainly mediated by dopamine [for review, see (24)]. While direct actions of (2*R*,6*R*)-HNK are a candidate for such improvements, its action as an antidepressant remains to be tested in humans, and links between this metabolite and anhedonia-related changes in brain activations have yet to be observed.

In this study, we aimed to investigate the effects of ketamine on task performance and functional brain response to the MID task 2 hours after infusion—the time at which early antidepressant effects are reported—in a cohort of participants with remitted depression. We chose to recruit treatment-free participants with remitted depression because they present with altered brain activations in reward-related areas (3,25,26) that might resemble those observed in depression and would allow the examination of ketamine's effects without the confounds of antidepressant treatment or concurrent symptom change. We have focused on specific regions of interest (ROIs) associated with reward processing that are activated during the MID task, namely, the striatum, ventral tegmental area (VTA), amygdala, and insula (2,9–12). We hypothesized that ketamine would increase activation in those areas. We also examined cortical areas associated with reward in an exploratory whole-brain analysis. The difference in the activation between ketamine and placebo in the sgACC was included in an exploratory, post hoc analysis. Moreover, we measured the levels of ketamine's metabolites to explore whether (2*R*,6*R*)-HNK levels correlate with any ketamine-related changes in the activation of reward processing brain areas.

METHODS AND MATERIALS

Participants

A total of 37 volunteers with remitted depression (21 female, mean age = 28.5 years) took part in a randomized, double-blind, placebo-controlled, crossover study. The Mini-International Neuropsychiatric Interview was used to confirm history of depression and remission at study entry. Inclusion criteria included a minimum of 3 months of no antidepressant treatment before taking part. Exclusion criteria included any history of other psychiatric or neurologic disorder; a previous adverse response to ketamine; any medical conditions that affect hepatic, renal, or gastrointestinal functions; cardiac abnormalities; hypertension; a significant history of substance abuse or a positive test for drugs of abuse at screening or a study day; use of nicotine (≥5 cigarettes per day), alcohol (≥28 units/week), or caffeine (≥6 cups per day); or any MRI contraindications. All participants gave written informed consent for the study, which was approved by the Psychiatry, Nursing and Midwifery Research Ethics Subcommittee (reference: HR-14/15-0650).

Study Procedures

Participants who met eligibility criteria were randomized to receive either a single intravenous infusion of ketamine (0.5 mg/kg) or placebo (0.9% saline solution) during the first session and the other treatment in the second session. Ketamine and saline were administered during a 40-minute steady-state infusion (27), and the sessions were at least 7 days apart. Participants were scanned 2 hours after the end of the infusion.

Scales and Questionnaires

The Psychotomimetic States Inventory was used to assess the psychotomimetic symptoms that ketamine might produce (28) and completed at the end of each infusion. A greater Psychotomimetic States Inventory score indicates more drug-induced psychotomimetic experiences.

The Snaith-Hamilton Pleasure Scale (SHAPS) was used to assess anhedonia at the beginning of each scanning session as well as 2 hours after each infusion (29). Owing to multiple administration during the study, instructions to the SHAPS were modified, asking participants to rate their ability to experience pleasure at the time of the assessment. Higher SHAPS scores indicate higher levels of anhedonia present.

Image Acquisition and Preprocessing

All scans were acquired using a GE MR750 3T scanner (GE Healthcare) and a 16-channel head coil. Functional scans were obtained using T2* sensitive gradient-echo echo-planar imaging (repetition time = 2000 ms, echo time = 30 ms, flip angle = 75°, field of view = 214 mm, slice thickness = 3 mm, number of slices = 42). The initial four volumes of each time series were discarded to minimize steady-state effects on the signal amplitude. A total of 414 volumes were analyzed for each time series acquired. A T1-weighted magnetization prepared rapid acquisition gradient-echo scan (field of view = 204 mm, repetition time = 7.3 ms, echo time = 3 ms, 256 × 256 × 156 matrix, slice thickness = 1.2 mm) was acquired on each session and was used for the reconstruction of a DARTEL template (30).

All structural and functional data were analyzed using SPM12. Preprocessing steps included realignment of the scans for each session as well as between sessions, coregistration to the magnetization prepared rapid acquisition gradient-echo image, and normalization using the DARTEL flow fields. The normalized images were then smoothed using an 8-mm full width at half maximum kernel. During the first-level modeling, the six motion parameters estimated during the realignment were used as regressors along with framewise displacement (31). One participant was excluded from the analysis owing to excessive movement—head motion exceeded 3 mm, and framewise displacement was no more than 1 mm. There were no significant differences (paired t test, $p > .05$) in the framewise displacement between the ketamine and placebo conditions (ketamine: mean framewise displacement ± SD = 0.091 ± 0.057 mm; placebo: mean framewise displacement ± SD = 0.083 ± 0.045 mm).

The MID Task

The version of the task closely followed that described in Knutson *et al.* (7) with a detailed description in the Supplement. The task consists of 96 trials of different reward magnitudes (high-win trials, low-win trials, neutral trials) signaled by the initial cue. The cue image is followed by a variable delay, after which a target appears on the screen and participants have to respond with a left button press. During the feedback phase, the outcome of the trial and the total amount won are presented to participants. For the anticipation phase of the task, 3 regressors were created corresponding to different reward magnitudes associated with the task cues: high-win anticipation, low-win anticipation, and neutral anticipation. The feedback phase of the win and no-win trials of the task were modeled separately and four regressors were created: high-win feedback, low-win feedback, high no-win feedback, and low no-win feedback. All the anticipation and feedback contrasts were examined separately for the ketamine and placebo session and compared between the two drug conditions. A more detailed description of the task and the contrasts that were examined for this study is included in the Supplement.

ROI Definition

The ROIs that we selected comprised the amygdala, ventral and dorsal striatum, VTA, and insula. The bilateral ROI for the ventral striatum (nucleus accumbens [NAc]) was defined as described in Montgomery *et al.* (32), based on previous work from Mawlawi *et al.* (33). The amygdala, dorsal striatum, VTA, and insula were anatomically defined using the FSL Harvard-Oxford atlas (34). The bilateral ROI for the sgACC was defined as in Morris *et al.* (21) and included Brodmann area 25. All ROIs were thresholded for gray matter with the minimal probability index set at 20% and binarized. The mean beta estimates from the first-level modeling were extracted for each ROI using MarsBaR. The ROI values were extracted for each subject and for each contrast for the ketamine and placebo sessions and were analyzed in SPSS version 25 (IBM Corp.).

Ketamine's Metabolites

Blood samples were collected at the beginning of each study session, immediately after the drug infusion, and 2 hours after the end of the infusion. Ketamine, norketamine, and the two isoforms of hydroxynorketamine [(2*R*,6*R*)-HNK; (2*S*,6*S*)-HNK] were measured in these samples. The values were used as a correlates with the ROI data to explore whether changes in brain activations induced by ketamine were related to the plasma exposure to ketamine and its main metabolites.

Statistical Analyses

The overall effect of treatment on each task contrast was examined using a mixed-effects model in SPSS. Each contrast was explored further by comparing the ROI activation between ketamine and placebo using a paired t test and within each treatment session by using a one-sample t test. Bonferroni correction for multiple comparisons was applied ($p = .008$).

To examine whether the ketamine metabolite levels 2 hours after infusion would predict the ROI activation under ketamine, we performed robust regressions. The placebo beta values were used as a covariate in this analysis to account for individual differences in brain activations, and false discovery rate (FDR) correction was applied.

RESULTS

Subjective Effects of Ketamine

The established increase in psychotomimetic effects on ketamine were shown with the Psychotomimetic States Inventory total score (ketamine = 48.4 ± 22.9; placebo = 15.1 ± 10.6) and 6 subscales (Figure 1). The immediate effects of ketamine were as expected, and the low placebo scores also aligned with expectations for this group of volunteers with remitted depression who did not experience any significant symptoms including anhedonia. This was also confirmed by the SHAPS, which, as expected, indicated very low levels of anhedonia before infusion (preplacebo score = 22.7 ± 5.6; preketamine score = 21.8 ± 5.4; Wilcoxon signed-rank test, $z = -0.811$, $p > .05$) that remained unchanged after ketamine (2-hours postketamine score = 21.9 ± 5.3; Wilcoxon signed-rank test, $z = -0.981$, $p > .05$).

The MID Task

Task Performance. The total amount of money won during the task did not significantly differ (paired t test, $p > .05$) between the ketamine and placebo sessions (ketamine = 45.1 ± 5.5; placebo = 43.3 ± 9.1). For reaction times, there was a

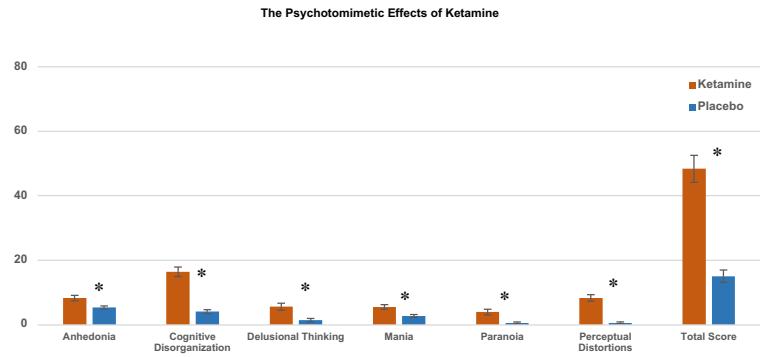

Figure 1. Ketamine administration produced robust psychotomimetic effects as measured by the Psychotomimetic States Inventory right after the infusion. Significant increases were observed in the total score as well as the six Psychotomimetic States Inventory subscales for the ketamine session compared with the placebo session (paired *t* test, $p < .05$). *Signifies a statistically significant difference between the ketamine and placebo groups.

	Anhedonia	Cognitive Disorganization	Delusional Thinking	Mania	Paranoia	Perceptual Distortions	Total Score
Ketamine	8.33(±4.6)	16.47(±8.1)	5.63(±6.0)	5.57(±3.9)	4.01(±4.7)	8.37(±5.6)	48.37(±22.9)
Placebo	5.43(±2.5)	4.10(±3.4)	1.47(±2.9)	2.77(±2.5)	0.66(±1.4)	0.67(±1.5)	15.1(±10.5)

main effect of reward magnitude with faster responses for high-win trials ($F_{2,36} = 23.2$, $p < .0001$) and no interaction with drug.

Brain Activations on Placebo. The brain activations during the anticipation and feedback phases of the MID task aligned with expectations based on previous studies (Figure S1).

Ketamine's Effects on the MID Task. For the whole-brain analyses, there were no differences between the ketamine and placebo sessions.

The a priori–defined ROIs were examined for all the contrasts that were created for the MID task, and here we present the specific contrasts for which ROI activation significantly changed between the ketamine and placebo sessions. The statistical values for the main effects are provided in the text and for the ROIs in the figures and legends.

Anticipation Phase. A main effect of ketamine increasing activity was identified for the anticipation of all win trials compared with neutral trials across the predefined ROIs ($F_{1,36} = 9.261$, $p = .003$). No main drug effect was identified when the anticipation phases of high- and low-win trials compared with neutral trials were examined separately or compared with each other. When individual ROIs were examined separately for each of the anticipation contrasts, ketamine produced significant changes in the NAc and caudate, when anticipation of high-win trials was contrasted to neutral trials (Figure 2A). This finding, however, did not survive testing for multiple comparisons.

Feedback Phase—Win Trials. A main effect of ketamine increasing activity was identified for the feedback phase of low-win trials compared with neutral trials across the predefined ROIs ($F_{1,36} = 4.563$, $p < .001$).

When the feedback phase of win trials was explored further, ketamine, compared with placebo, increased activations in the NAc and the putamen during the feedback phase of low-win trials compared with neutral trials (Figure 2B). This effect survived correction for multiple comparisons.

Feedback Phase—No-Win Trials. A main effect of ketamine, across all predefined ROIs, was observed when the feedback phase of all the no-win trials was contrasted to the neutral trials ($F_{1,36} = 5.467$, $p < .001$) and when the feedback phase of high no-win trials was compared with neutral trials ($F_{1,36} = 5.859$, $p = .016$). For individual ROIs, none of these effects survived correction for multiple comparisons (Figure 2C–E).

Feedback Phase—Win Trials Versus No-Win Trials. A main effect of ketamine was identified across all predefined ROIs when all the win trials were compared with the no-win trials ($F_{1,36} = 5.036$, $p < .001$), but no single ROI showed a significant change by itself after correction for multiple comparisons (Figure 2F).

Association of ROI Activation With (2R,6R)-HNK Levels. A positive correlation was identified, using robust regression, between the VTA activation 2 hours after ketamine infusion and the plasma levels of (2*R*,6*R*)-HNK, 2 hours after the ketamine infusion ($n = 22$, $p_{FDR} = .03$). This correlation was identified when the feedback phase of low-win trials was contrasted to that of neutral trials (Figure 3). A positive correlation was also identified for the activation of the caudate 2 hours after ketamine infusion and the plasma levels of (2*R*,6*R*)-HNK when high no-win trials were contrasted to neutral trials. This finding did not survive testing for multiple comparisons.

There were no relationships between ROI values and ketamine, norketamine, and (2*S*,6*S*)-HNK plasma levels for any of the task contrasts.

Exploratory Analysis. Ketamine did not produce any significant changes in the activation of the sgACC 2 hours after administration in any of the task contrasts that were examined. The results of this analysis are presented in Figure S2.

DISCUSSION

Ketamine, approximately 2 hours after its administration, modulated brain activity during the MID task, in areas that are important for reward processing. To our knowledge, our study

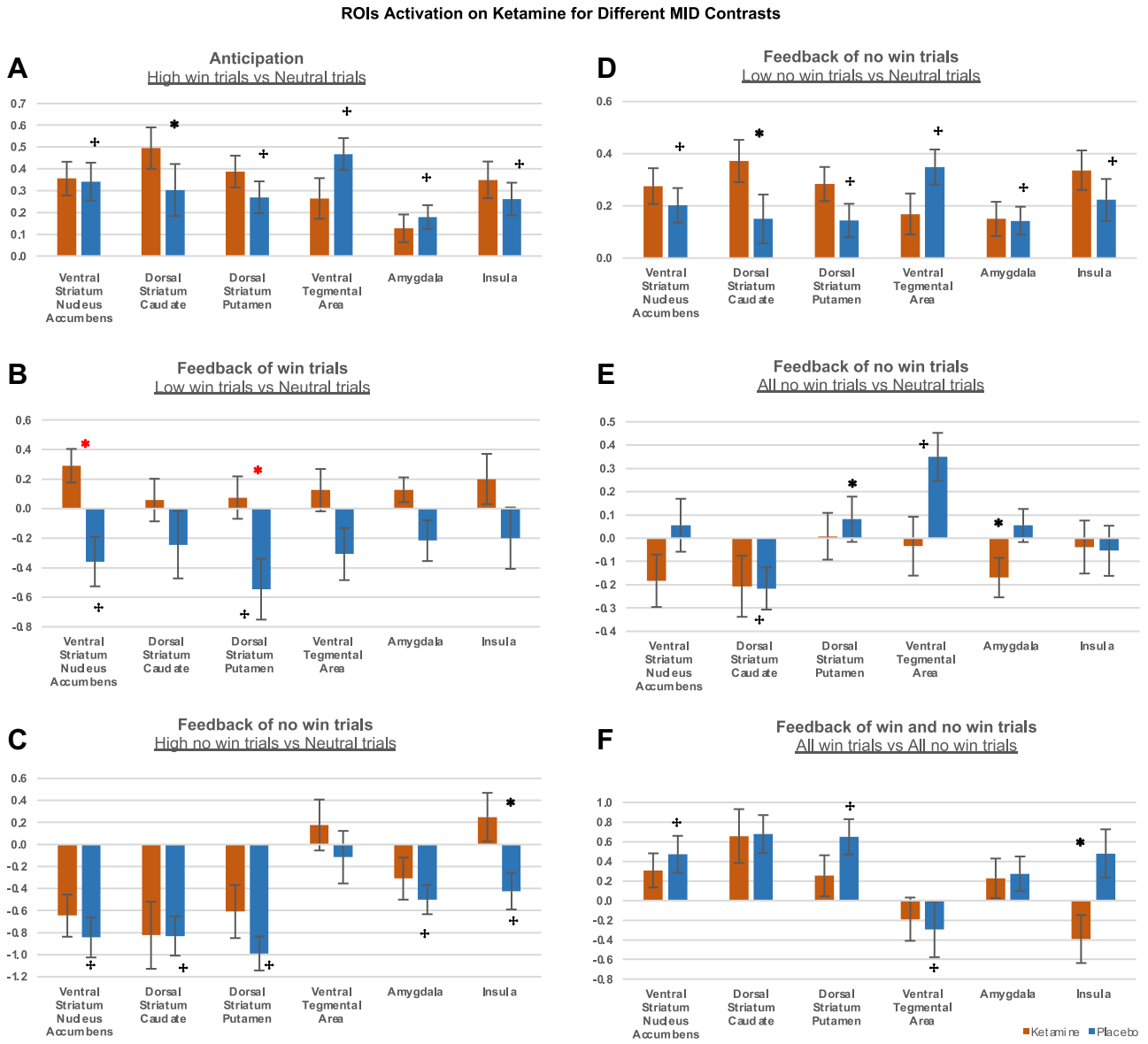

Figure 2. The activation of our predefined regions of interest (ROIs) was examined for the anticipation **(A)** and feedback phase of the high- and low-win and no-win trials **(B–F)**. The beta values extracted for each contrast were compared between the ketamine and placebo sessions. All significant comparisons (paired *t* test, $p < .05$) are indicated with an asterisk. When the feedback phase of the low-win trials was contrasted to the feedback phase of neutral trials, the ventral striatum/nucleus accumbens and the dorsal striatum/putamen presented with significant increases 2 hours after ketamine compared with placebo **(B)**, and this result survived Bonferroni correction for multiple comparisons ($p_{CORR} = .008$), indicated with a red asterisk. The ROIs that were significantly activated ($p_{FDR\_CORR} < .05$) for the same contrast in the placebo session alone are indicated with a cross. The task activations under placebo are presented in more detail in the Supplement. MID, monetary incentive delay. FDR CORR, false discovery rate-corrected.

is the first to demonstrate that ketamine can produce detectable changes in the activation of brain areas that are important for reward processing and anhedonia 2 hours after infusion without concurrent changes in depressive symptoms and the confounding effects of antidepressant treatment.

Previous studies have shown that ketamine, 24 hours after its administration, normalizes some of the connectivity changes observed in depression (35, 36) and reduces hyperactivation in the sgACC during a reward-processing task (21). All these effects, at the time point when they were observed, were accompanied by improvements in depressive symptoms and thus either could be attributed to the primary effects of the drug on neural processes that are affected in depression or could be the secondary effect of symptom changes that ketamine produces. In our cohort of volunteers with remitted depression, depressive symptoms and anhedonia were not present and did not change with ketamine, suggesting that the drug can directly modulate reward-related neural processes

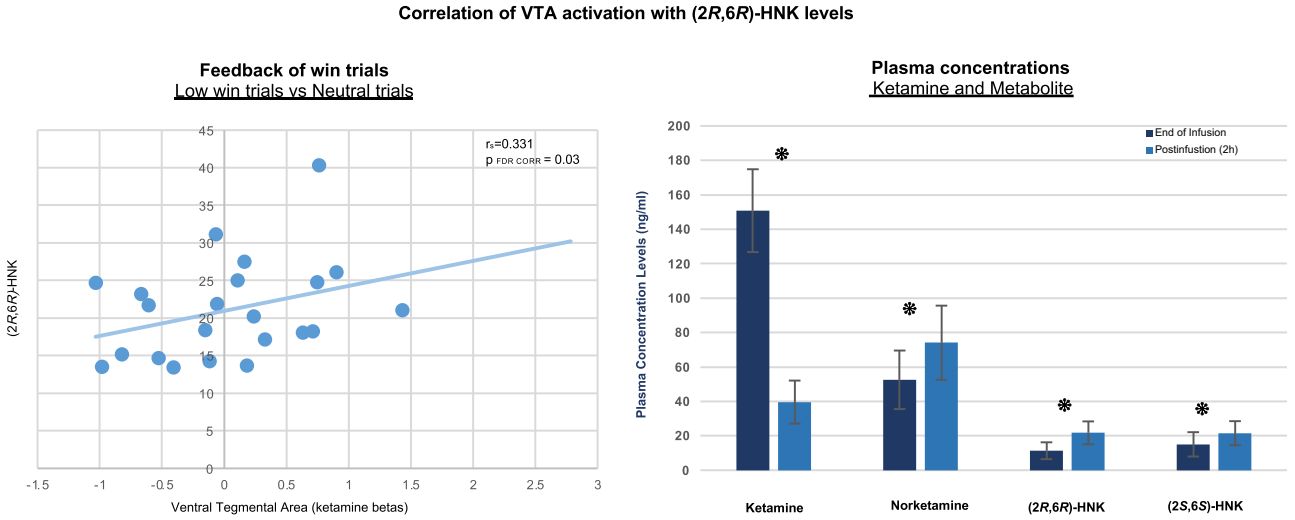

Figure 3. **(A)** The levels of (2*R*,6*R*)-HNK, as measured 2 hours after infusion, significantly correlated (r_s = 0.33, p = .03) with the activation (beta values) of the ventral tegmental area (VTA) during the ketamine session and when the feedback phase of low-win trials was contrasted to that of neutral trials. This finding remained significant ($p_{FDR\ CORR}$ = .033) when a robust regression was performed using the placebo beta values as a covariate to account for individual differences in brain activation during that contrast. **(B)** The blood concentrations for ketamine and its main metabolites were measured at the end of the 40-minute infusion and 2 hours after infusion. FDR CORR, false discovery rate-corrected.

(17,18,21), producing differential effects depending on the task contrast.

Ketamine increased the activation of the NAc, putamen, insula, and caudate when the feedback phase of win and no-win trials was compared with that of neutral trials (Figure 1B–D). Recent meta-analyses have shown that striatal regions present with decreased activations during the anticipation and feedback phase of the MID task in patients with a mixture of mood disorders (2,12). Moreover, striatal hypofunction persists during remission (15), and altered brain activations in those areas could also contribute to the blunted responses to positive feedback that characterize individuals with remitted depression (37). Individuals with remitted depression and individuals with depression also demonstrate heightened neural responses to negative feedback (38), which has been related to anhedonia.

The fact that ketamine, during the feedback phase of the MID task, approximately 2 hours after administration, altered the activation within the mesolimbic reward pathway provides a plausible mechanism by which ketamine could modulate abnormal responses to positive and negative feedback. In addition, ketamine's effects are more prominent for the feedback phase of no-win trials, which could indicate that the drug increases the salience of these trials in our cohort of those with remitted depression. This effect could increase motivation especially in relation to no-win trials and be beneficial for anhedonia. Several of the brain areas where ketamine-induced alterations were observed in our study are also target areas for antidepressant treatments with different pharmacology (39), and changes in their activation and connectivity predict treatment response (40,41). Taken together, these findings indicate that the effects observed in our study 2 hours after ketamine administration could be relevant to the improvement of symptoms in depression. However, to fully understand the consequence of these changes in the modulation of specific symptoms such as anhedonia and guilt (38), studies in patients with active depression will be needed.

In our study, we found preliminary evidence to link the changes in brain activity with the levels of an active metabolite of ketamine, (2*R*,6*R*)-HNK. The increases in brain activity in the VTA during the feedback phase of low-win trials positively correlated with the levels of (2*R*,6*R*)-HNK. Increased VTA activity during the feedback phase of a task that does not involve new learning is rather unexpected. It is possible that ketamine might increase sensitivity to negative feedback. As a result, the negative outcomes of the no-win trials would be perceived as unexpected and trigger new learning, which would be associated with increased activation of the VTA (42,43). The increased plasticity accompanying ketamine's antidepressant action might also be contributing to that effect.

It has been suggested that direct activation of AMPA receptors by (2*R*,6*R*)-HNK triggers the plasticity-related pathways, mediating ketamine's antidepressant action (23). Brain areas of the mesolimbic pathway receive dense glutamatergic input, and glutamate receptors of this pathway are crucial for synaptic plasticity (44). While there is no direct evidence of increased plasticity after ketamine in patients, positron emission tomography studies support this conclusion through increased glucose metabolism, which correlates with improvements in depression symptoms and anhedonia in the ventral striatum, dorsal anterior cingulate cortex, and putamen 2 hours after infusion (17,18). Taken together with studies of Lally *et al.* (17,18), our findings demonstrate the potential value of concurrent measurement of brain metabolism, functional modulation of brain activity, symptom changes, and metabolites levels in building a model of the effects of ketamine in improving specific symptoms.

This study has a number of limitations. First, the absence of a healthy volunteer group does not allow the direct

characterization of impairments in reward processing in our remitted group and thus does not establish whether the effect of ketamine is toward a normalization of these changes. In addition, to our knowledge, no other study has looked at the effects of ketamine in reward processing 2 hours after administration in healthy volunteers, which might assist with the interpretability of our findings.

Second, most of the ketamine-associated changes have been identified during the feedback phase of the MID task, highlighting the role of positive and negative outcomes for reward processing and anhedonia. The strength of the MID task design is in the reward anticipation phase with fewer trials contributing to the feedback contrasts; thus, future studies using a reward task designed to focus on outcomes will help in replicating the feedback effects, as well the potential relationships with anticipation effects. While it remains possible that the effects during feedback are a consequence of the drug effects during anticipation, this is unlikely because both increases and decreases in activity were observed during feedback on ketamine versus placebo. These differential effects also do not fit with an interpretation of the drug effect being understood as a change in neurovascular coupling. In addition, in our results, we observed that ketamine has differential effects during the feedback phase of win and no-win trials, potentially indicating that the drug might produce more profound effects during the no-win condition or even punishment. Our version of the MID task does not have a loss condition and thus does not allow us to determine the specificity of our effects during reward trials or explore any potential effects that ketamine might have when monetary rewards are lost instead of not gained by participants. Future studies that are better powered to look at feedback, including loss and no win as well win trials, are needed to address this question.

In summary, this study demonstrates that ketamine, 2 hours after administration, could produce detectable changes in brain areas that are part of the mesolimbic pathway involved in reward processing. These changes were not secondary to symptom changes in our cohort of volunteers with remitted depression. During the feedback phase of low-win and high no-win trials, changes in brain activity correlate with the levels of (2*R*,6*R*)-HNK. These findings support a model whereby ketamine improves reward processing deficits via enhanced anticipation of reward and modulation of responses to negative feedback and also highlight the importance of the drug metabolite levels in understanding ketamine's antidepressant and antianhedonic actions. Future studies examining the role of ketamine's metabolites during reward processing task in depression would contribute to our understanding of ketamine's antidepressant action.

ACKNOWLEDGMENTS AND DISCLOSURES

The research reported in this article was supported by grants from Johnson & Johnson awarded to University College London (HVC) and King's College London (Grant No. 23034 [to MAM, AS]). This paper represents independent research part-supported by a scholarship supported from the National Institute for Health Research (NIHR) Biomedical Research Centre at South London and Maudsley National Health Service (NHS) Foundation Trust and King's College London (to MAM, VK). The views expressed are those of the authors and not necessarily those of the NHS, the NIHR, or the Department of Health and Social Care.

We would like to thank the Centre for Neuroimaging Sciences' research staff for all their hard work and support throughout this research project.

HVC's research is supported by the UK Medical Research Council and NIHR; she has consulted for Janssen on esketamine. MAM has received funding from Johnson & Johnson, Lundbeck, and Takeda and has acted as a consultant for Lundbeck and Takeda. MF is an employee of Janssen Research and Development. All other authors report no biomedical financial interests or potential conflicts of interest.

ClinicalTrials.gov: Ketamine's Actions on Rumination Mechanisms as an Antidepressant (KARMA); https://clinicaltrials.gov/ct2/show/NCT04656886; NCT04656886.

ARTICLE INFORMATION

From the Department of Neuroimaging (VK, NM, NB, PCTH, MAM), Institute of Psychiatry, Psychology and Neuroscience, King's College London; Clinical Psychopharmacology Unit (HVC), University College London, London, United Kingdom; Mood Brain and Development Unit (AS), Emotion and Development Branch, National Institute of Mental Health, National Institutes of Health, Bethesda, Maryland; and Janssen Pharmaceuticals of Johnson & Johnson Inc. (MF), San Diego, California.

Address correspondence to Vasileia Kotoula, Ph.D., at vasileia.kotoula@kcl.ac.uk.

Received Mar 14, 2021; revised Apr 26, 2021; accepted May 23, 2021.

Supplementary material cited in this article is available online at https://doi.org/10.1016/j.bpsc.2021.05.009.

REFERENCES

1. Whitton AE, Treadway MT, Pizzagalli DA (2015): Reward processing dysfunction in major depression, bipolar disorder and schizophrenia. Curr Opin Psychiatry 28:7–12.
2. Keren H, O'Callaghan G, Vidal-Ribas P, Buzzell GA, Brotman MA, Leibenluft E, *et al.* (2018): Reward processing in depression: A conceptual and meta-analytic review across fMRI and EEG studies. Am J Psychiatry 175:1111–1120.
3. Pechtel P, Dutra SJ, Goetz EL, Pizzagalli DA (2013): Blunted reward responsiveness in remitted depression. J Psychiatr Res 47:1864–1869.
4. Schiller CE, Minkel J, Smoski MJ, Dichter GS (2013): Remitted major depression is characterized by reduced prefrontal cortex reactivity to reward loss. J Affect Disord 151:756–762.
5. Murrough JW, Soleimani L, DeWilde KE, Collins KA, Lapidus KA, Iacoviello BM, *et al.* (2015): Ketamine for rapid reduction of suicidal ideation: A randomized controlled trial. Psychol Med 45:3571–3580.
6. Argyropoulos SV, Nutt DJ (2013): Anhedonia revisited: Is there a role for dopamine-targeting drugs for depression? J Psychopharmacol 27:869–877.
7. Knutson B, Westdorp A, Kaiser E, Hommer D (2000): FMRI visualization of brain activity during a monetary incentive delay task. Neuroimage 12:20–27.
8. Arias-Carrión O, Stamelou M, Murillo-Rodríguez E, Menéndez-González M, Pöppel E (2010): Dopaminergic reward system: A short integrative review. Int Arch Med 3:24.
9. Wilson RP, Colizzi M, Bossong MG, Allen P, Kempton M, MTAC, Bhattacharyya S (2018): The neural substrate of reward anticipation in health: A meta-analysis of fMRI findings in the monetary incentive delay task. Neuropsychol Rev 28:496–506.
10. Oldham S, Murawski C, Fornito A, Youssef G, Yücel M, Lorenzetti V (2018): The anticipation and outcome phases of reward and loss processing: A neuroimaging meta-analysis of the monetary incentive delay task. Hum Brain Mapp 39:3398–3418.
11. Ng TH, Alloy LB, Smith DV (2019): Meta-analysis of reward processing in major depressive disorder reveals distinct abnormalities within the reward circuit. Transl Psychiatry 9:293.

12. Zhang B, Lin P, Shi H, Öngür D, Auerbach RP, Wang X, *et al.* (2016): Mapping anhedonia-specific dysfunction in a transdiagnostic approach: An ALE meta-analysis. Brain Imaging Behav 10:920–939.
13. Nielson DM, Keren H, O'Callaghan G, Jackson SM, Douka I, Vidal-Ribas P, *et al.* (2021): Great expectations: A critical review of and suggestions for the study of reward processing as a cause and predictor of depression. Biol Psychiatry 89:134–143.
14. Stringaris A, Vidal-Ribas Belil P, Artiges E, Lemaitre H, Gollier-Briant F, Wolke S, *et al.* (2015): The brain's response to reward anticipation and depression in adolescence: Dimensionality, specificity, and longitudinal predictions in a community-based sample. Am J Psychiatry 172:1215–1223.
15. Hammar Å., Neto E, Clemo L, Hjetland GJ, Hugdahl K, Elliott R (2016): Striatal hypoactivation and cognitive slowing in patients with partially remitted and remitted major depression. Psych J 5:191–205.
16. Krystal AD, Pizzagalli DA, Smoski M, Mathew SJ, Nurnberger J Jr, Lisanby SH, *et al.* (2020): A randomized proof-of-mechanism trial applying the 'fast-fail' approach to evaluating kappa-opioid antagonism as a treatment for anhedonia. Nat Med 26:760–768.
17. Lally N, Nugent AC, Luckenbaugh DA, Ameli R, Roiser JP, Zarate CA (2014): Anti-anhedonic effect of ketamine and its neural correlates in treatment-resistant bipolar depression. Transl Psychiatry 4:e469.
18. Lally N, Nugent AC, Luckenbaugh DA, Niciu MJ, Roiser JP, Zarate CA Jr (2015): Neural correlates of change in major depressive disorder anhedonia following open-label ketamine. J Psychopharmacol 29:596–607.
19. Husain M, Roiser JP (2018): Neuroscience of apathy and anhedonia: A transdiagnostic approach. Nat Rev Neurosci 19:470–484.
20. Alexander L, Gaskin PLR, Sawiak SJ, Fryer TD, Hong YT, Cockcroft GJ, *et al.* (2019): Fractionating blunted reward processing characteristic of anhedonia by over-activating primate subgenual anterior cingulate cortex. Neuron 101:307–320.e6.
21. Morris LS, Costi S, Tan A, Stern ER, Charney DS, Murrough JW (2020): Ketamine normalizes subgenual cingulate cortex hyper-activity in depression. Neuropsychopharmacology 45:975–981.
22. Yang C, Yang J, Luo A, Hashimoto K (2019): Molecular and cellular mechanisms underlying the antidepressant effects of ketamine enantiomers and its metabolites. Transl Psychiatry 9:280.
23. Zanos P, Moaddel R, Morris PJ, Georgiou P, Fischell J, Elmer GI, *et al.* (2016): NMDAR inhibition-independent antidepressant actions of ketamine metabolites. Nature 533:481–486.
24. Rincón-Cortés M, Grace AA (2020): Antidepressant effects of ketamine on depression-related phenotypes and dopamine dysfunction in rodent models of stress. Behav Brain Res 379:112367.
25. Whitton AE, Kakani P, Foti D, Van't Veer A, Haile A, Crowley DJ, Pizzagalli DA (2016): Blunted neural responses to reward in remitted major depression: A high-density event-related potential study. Biol Psychiatry Cogn Neurosci Neuroimaging 1:87–95.
26. Geugies H, Mocking RJT, Figueroa CA, Groot PFC, Marsman JC, Servaas MN, *et al.* (2019): Impaired reward-related learning signals in remitted unmedicated patients with recurrent depression. Brain 142:2510–2522.
27. Murrough JW, Perez AM, Pillemer S, Stern J, Parides MK, aan het Rot M, *et al.* (2013): Rapid and longer-term antidepressant effects of repeated ketamine infusions in treatment-resistant major depression. Biol Psychiatry 74:250–256.
28. Mason OJ, Morgan CJ, Stefanovic A, Curran HV (2008): The psychotomimetic states inventory (PSI): Measuring psychotic-type experiences from ketamine and cannabis. Schizophr Res 103:138–142.
29. Snaith RP, Hamilton M, Morley S, Humayan A, Hargreaves D, Trigwell P (1995): A scale for the assessment of hedonic tone the Snaith-Hamilton Pleasure Scale. Br J Psychiatry 167:99–103.
30. Ashburner J (2007): A fast diffeomorphic image registration algorithm. Neuroimage 38:95–113.
31. Siegel JS, Power JD, Dubis JW, Vogel AC, Church JA, Schlaggar BL, Petersen SE (2014): Statistical improvements in functional magnetic resonance imaging analyses produced by censoring high-motion data points. Hum Brain Mapp 35:1981–1996.
32. Montgomery AJ, Mehta MA, Grasby PM (2006): Is psychological stress in man associated with increased striatal dopamine levels?: A [11C] raclopride PET study. Synapse 60:124–131.
33. Mawlawi O, Martinez D, Slifstein M, Broft A, Chatterjee R, Hwang DR, *et al.* (2001): Imaging human mesolimbic dopamine transmission with positron emission tomography: I. Accuracy and precision of D(2) receptor parameter measurements in ventral striatum. J Cereb Blood Flow Metab 21:1034–1057.
34. Desikan RS, Ségonne F, Fischl B, Quinn BT, Dickerson BC, Blacker D, *et al.* (2006): An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. Neuroimage 31:968–980.
35. Abdallah CG, Averill LA, Collins KA, Geha P, Schwartz J, Averill C, *et al.* (2017): Ketamine treatment and global brain connectivity in major depression. Neuropsychopharmacology 42:1210–1219.
36. Evans JW, Szczepanik J, Brutsché N, Park LT, Nugent AC, Zarate CA Jr (2018): Default mode connectivity in major depressive disorder measured up to 10 days after ketamine administration. Biol Psychiatry 84:582–590.
37. McCabe C, Mishor Z, Cowen PJ, Harmer CJ (2010): Diminished neural processing of aversive and rewarding stimuli during selective serotonin reuptake inhibitor treatment. Biol Psychiatry 67:439–445.
38. Martin-Soelch C (2009): Is depression associated with dysfunction of the central reward system? Biochem Soc Trans 37:313–317.
39. Stoy M, Schlagenhauf F, Sterzer P, Bermpohl F, Hägele C, Suchotzki K, *et al.* (2012): Hyporeactivity of ventral striatum towards incentive stimuli in unmedicated depressed patients normalizes after treatment with escitalopram. J Psychopharmacol 26:677–688.
40. Avissar M, Powell F, Ilieva I, Respino M, Gunning FM, Liston C, Dubin MJ (2017): Functional connectivity of the left DLPFC to striatum predicts treatment response of depression to TMS. Brain Stimul 10:919–925.
41. Salomons TV, Dunlop K, Kennedy SH, Flint A, Geraci J, Giacobbe P, Downar J (2014): Resting-state cortico-thalamic-striatal connectivity predicts response to dorsomedial prefrontal rTMS in major depressive disorder. Neuropsychopharmacology 39:488–498.
42. Ranaldi R (2014): Dopamine and reward seeking: The role of ventral tegmental area. Rev Neurosci 25:621–630.
43. Saunders BT, Richard JM (2011): Shedding light on the role of ventral tegmental area dopamine in reward. J Neurosci 31:18195–18197.
44. Eisenhardt M, Leixner S, Luján R, Spanagel R, Bilbao A (2015): Glutamate receptors within the mesolimbic dopamine system mediate alcohol relapse behavior. J Neurosci 35:15523–15538.