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ORIGINAL PAPER

Remembering pleasure and personal meaning from episodes of intrinsic motivation: an fMRI study

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Abstract
To decide whether or not to participate in an upcoming activity, people can use their memories of intrinsically-motivating or non-intrinsically-motivating experiences during previous participations. To understand the underlying neural mechanism of intrinsic motivation memories, we used a block-design functional magnetic resonance imaging (fMRI) experiment to compare the neural activations during intrinsically-motivating memories versus during non-intrinsically-motivating memories. Results showed that both the ventromedial prefrontal cortex (VMPFC) and anterior cingulate cortex (ACC) were more activated during the recall of intrinsically-motivating memories rather than during the recall of non-intrinsically-motivating memories. Greater negative functional interactions between the VMPFC and ACC were also observed in the intrinsically-motivating situations. These findings suggest that the two complementary neural processes are employed to reconstruct intrinsically-motivating experiences: pleasure (reward related to VMPFC activity) and personal meaning (self-endorsement related to ACC activity).

Keywords Anterior cingulate cortex (ACC) · Functional magnetic resonance imaging (fMRI) · Intrinsic motivation · Self-determination theory (SDT) · Ventromedial prefrontal cortex (VMPFC)

Introduction

Intrinsic motivation arises out of experiences of psychological need satisfaction to represent the positive emotionality (i.e., interest and enjoyment) that experiences of autonomy, competence, and relatedness satisfaction generate (Ryan and Deci 2017). When people engage in activities that generate psychologically need-satisfying experiences, they experience intrinsic motivation and this experience of intrinsic motivation is associated with a wide range of indicators of positive functioning, including engagement, learning, creativity, performance, vitality, and well-being (Chen et al. 2015; Jang et al. 2012; Reis et al. 2000; Taylor and Lonsdale 2010; Vansteenkiste et al. 2004). The benefits of intrinsic motivation during task engagement are well documented (Ryan and Deci 2017), but it is further worth noting that people remember whether the activity was intrinsically-motivating or not for them (Krapp 2005; Reeve et al. 2015). These memories are important because they affect the decision-making whether to seek out and reengage in that activity in the future (Deci et al. 1999). That is, when people have another opportunity to engage with the activity or not, intrinsic motivation memories would tip that person's decision-making toward reengaging the same or similar tasks, activities, or situations. Intrinsic motivation memories might also encourage exploratory behavior for that same or similar task, activity, or situation in a free-choice situation (e.g., free time on a Saturday afternoon) (Flum and Kaplan 2006). It therefore becomes an interesting question to ask what sort of neural information people are accessing when they recall the intrinsically-motivating episodes in their life.

The number of studies examining the neural mechanism of intrinsic motivation has steadily increased (Di Domenico and Ryan 2017; Reeve and Lee 2019a). From these neuroscience studies, researchers have found that the brain regions such as the striatum, ventromedial prefrontal cortex

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(VMPFC), anterior insula, and anterior cingulate cortex (ACC) play critical roles during the on-going experiences of intrinsic motivation. The striatum and VMPFC react to rewarding stimuli or situations, integrate and store pleasurable information from the rewarding experiences, and utilize that information during decision-making (Haber and Knutson 2010; McClure et al. 2004; O'Doherty 2004). Thus, reward processing is suggested as one of the key neural processes for intrinsic motivation. In addition, the anterior insula and ACC are known to work for self-based processes which influence the monitoring, interpretation, and representation of information from the external world (Craig 2009; Lee 2017; Northoff and Hayes 2011; Reeve and Lee 2019a). What is monitored, interpreted, and represented in the anterior insula and ACC is not pleasurable information and reward processing but, rather, the pursuit of personal interests, sense of agency, and strivings central to personal meaning. Therefore, self-endorsed processing is suggested as a second key process for intrinsic motivation.

The neural activation patterns observed during the on-going experiences of intrinsic motivation correspond to the theoretical postulates of intrinsic motivation. According to self-determination theory (SDT; Ryan and Deci, 2017; Vansteenkiste et al. 2010, 2020), people inherently possess basic psychological needs (i.e., autonomy, competence, relatedness). Because people experience intrinsic motivation as need satisfaction experiences (e.g., "I enjoyed that activity, because it allowed me to feel high competence satisfaction while doing it."), the satisfaction of these psychological needs are generally perceived as intrinsic rewards (i.e., hedonic pleasure). Because the psychological needs are conceptualized as intrinsic rewards, the involvement of the striatum and VMPFC, associated with reward processing (Haber and Knutson 2010), during the experience of intrinsic motivation is reasonable. The recruitment of anterior insula and ACC activities, associated with self-related processing (Enzi et al. 2009), is also understandable as intrinsic motivation is based on pursuing personal interests, self-endorsing one's actions, and doing that which creates personal meaning (i.e., eudaimonic purpose) (Ryan et al. 2013; Ryan and Huta 2009).

While several neuroscience studies exist about the on-going experiences of intrinsic motivation (Lee and Reeve 2017; Leotti and Delgado 2011, 2014; Murayama et al. 2010), neuroscience studies about the retrospective memories of intrinsic motivation are sparse. What does exist in the literature are studies that observe neural activations during the imagination of intrinsically-motivating behaviors (Lee and Reeve 2013; Lee et al. 2012). In these studies, participants were asked to imagine that they acted on described situations (e.g., imagining writing a paper on a very interesting topic) because the imagination of behaviors is known to activate the brain regions generally observed during their actual enactment (Ruby and Decety 2001). Though this experimental paradigm requested participants' imagination, this imagination was not about previous memories but about on-going simulated experiences. Considering that intrinsic motivation memories significantly influence subsequent decisions and behaviors (Jang et al. 2012; Murayama et al. 2010), it is important to understand the neural mechanism related to retrospective memories of intrinsic motivation.

The neural findings about episodic memories in general help understand the neural mechanism of remembering episodes of intrinsic motivation. According to Moscovitch et al. (2016), episodic memory is dynamic. Different neural structures accompany different types of memory transformations, such as core features of an episodic memory becoming more core over time while detail features become lost over time. Cortical brain regions (e.g., VMPFC, ACC, parietal brain regions) underlie core features of episodic memories, while subcortical brain regions (e.g., hippocampus) underlie detailed features. What remains from this on-going memory transformation process is the "gist-like" memories that are used for subsequent decisions and behaviors (Moscovitch et al. 2016; Wagner et al. 2005). This "gist-like" transformation seems to be recruited during the retrieval processes of intrinsic motivation memories.

In the present study, we sought to identify the neural substrates of intrinsic motivation memories. In particular, we compared the neural activations when participants remembered and imagined intrinsically-motivating situations vs. when participants remembered and imagined non-intrinsically-motivating situations. We hypothesized that the neural circuits related to (a) reward processing such as the VMPFC and striatum and (b) self-endorsement such as the ACC and anterior insula would both play critical roles during intrinsic motivation memories. In addition, we sought to identify the neural similarities and differences between the retrospective memories of intrinsic motivation (found in the present study) and on-going experiences of intrinsic motivation (reported in previous investigations).

Method

Participants

Eighteen Korean undergraduates (9 females and 9 males; mean age 22.9 ± 2.98 years), who were recruited from a large private university, participated in the functional magnetic resonance imaging (fMRI) study. Our sample size was similar to the sample sizes used in previous fMRI studies of intrinsic motivation (Gruber et al. 2014; Huskey et al. 2018). All participants were right-handed and had no history of neurological illness. The participants provided informed consent and received compensation for their participation.

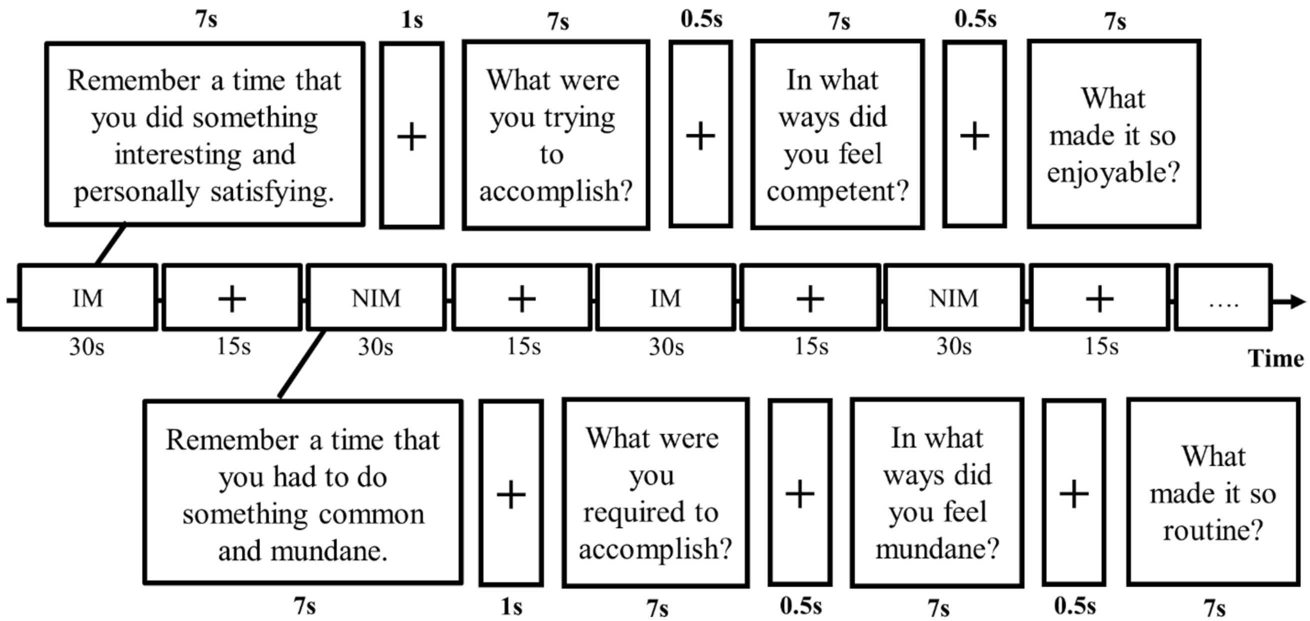

Fig. 1 In each task block, a 7-s introduction and three 7-s memory-provoking questions were given. Between the introduction and question stimuli, 500- or 1000-ms fixations were presented. Before the next task block for another condition begun, a 15-s fixation block was presented. IM: intrinsic motivation memories, NIM: non-intrinsic motivation memories

This study was approved by the university's Institutional Review Board.

Task and procedure

A Block-design fMRI experiment was conducted. The experimental task consisted of two separate runs and lasted 14 min in total. There were 9 task blocks for the intrinsic motivation condition and 9 task blocks for the non-intrinsic motivation condition, and these task blocks alternated between the two conditions. Block sequences were predetermined and counterbalanced between participants. The sequences of blocks and of stimuli for each task block are presented in Fig. 1.

In each task block, participants were asked to remember intrinsic motivation or non-intrinsic motivation memories. To help participants retrieve previous memories, an introduction was given for 7 s and then three 7-s memory-provoking questions were additionally given. In each task block, different memory-provoking questions were used. For example, in the case of intrinsic motivation memories, the memory-provoking questions asked about core features of intrinsically-motivating experiences, such as "interesting", "personally satisfying", "competent", and "enjoyable". In the case of non-intrinsic motivation memories, the memory-provoking questions asked about the features of non-intrinsically-motivating experiences, such as "mundane", "routine", and "required to do". All memory-provoking questions are presented in Table 1. Between the introduction and these question stimuli, 500- or 1000-ms fixations were presented. In this way, each task block lasted 30 s. Before the next task block begun, a 15-s fixation block was presented. A pilot test was conducted to anticipate the types of intrinsically-motivated and non-intrinsically-motivated activities participants would recall. The results from participants' self-reports showed that examples of intrinsically-motivating memories included enjoying a hobby, completing a competence-satisfying project, and taking a trip with close friends. In contrast, examples of non-intrinsically-motivating memories included preparing for a routine day at work, trying to manage a tight budget, and spending time on a daily chore.

Participants received the task instruction before entering the fMRI scanning room. During the brain scanning, functional images were obtained while participants performed the experimental task, and then structural images were obtained. Participants were debriefed about the experiment after the experiment was completed.

fMRI data acquisition

For functional and structural scanning, a 3 T Trio MRI scanner (Siemens, Erlangen, Germany) was used. 32-slice functional images were acquired using a T2*-weighted gradient-echo echo planar imaging (EPI) sequence sensitive to blood oxygenation level-dependent (BOLD) contrast (TR = 2000 ms, TE = 30 ms, flip angle = 90°, field of view = 224 × 224, in-plane resolution = 3.5 × 3.5 mm, slice thickness = 4 mm with no gap). After obtaining functional

Table 1 Memory-provoking instructions and questions for the intrinsic motivation and non-intrinsic motivation conditions (translated from the original Korean)

	Intrinsic motivation questions	Non-intrinsic motivation questions
Common instruction	Remember a time that you did something interesting and personally satisfying	Remember a time that you had to do something common and mundane
Question: Set 1	What were you trying to accomplish?	What were you required to accomplish?
	In what ways did you feel competent?	In what ways did you feel mundane?
	What made it so enjoyable?	What made it so routine?
Question: Set 2	What was new and different?	What was old and the same?
	What were you newly exploring?	What were you repeating over-and-over?
	Why was it important to you?	Why was it necessary for you to get done?
Question: Set 3	Did pursuing the goal allow you to feel you're your "true self"?	Did pursuing the goal allow you to fulfill a requirement?
	Why did you feel free?	What made it chore-like?
	Were you free to do things in your own way?	What responsibilities did you have to fulfill?
Question: Set 4	What was the activity?	What was the activity?
	What were you striving for?	What were you required to do?
	What was so interesting?	What was so repetitive?
Question: Set 5	What initiative did you show?	What routine did you complete?
	What made you feel energetic and alive?	What lessened your energy and enthusiasm?
	What made you so deeply satisfied?	What made it so common-place?
Question: Set 6	What progress did you seek to attain?	What requirement did you seek to fulfill?
	What progress did you expect to make?	What did you have to complete?
	What skills did you need to master?	In what ways did you feel relief?
Question: Set 7	What relationship was enriched?	What relationship was neglected?
	In what ways were you closer to family or friends?	In what ways did you gain financially?
	In what positive ways did you contribute to your community?	In what ways did you gain in status or popularity?
Question: Set 8	Who supported and encouraged you?	Who neglected or ignored you?
	What did this supportive person do for you?	What blocked you in your pursuit of goals?
	What did this supportive person say to you?	Did anyone interfere with your goal pursuit?
Question: Set 9	In what ways did you grow as a person?	In what ways were you stuck in a routine?
	What interesting experience was to happen?	What everyday experience was to happen?
	How did the experience help make you a better person?	How did the experience help others see you as a successful person?

images, we acquired high-resolution T1-weighted structural images using a MP-RAGE sequence (TR = 1900 ms, TE = 2.52 ms, flip angle = 9°, field of view = 256 × 256, in-plane resolution = 1 × 1 mm, slice thickness = 1 mm with no gap). The structural images were used for anatomical localization to facilitate the precise determination of the structures corresponding to the functional activation foci.

fMRI data analysis

AFNI (Cox 1996; https://afni.nimh.nih.gov) was used for brain image analyses. The first three images of each run were discarded to make hemodynamics and MRI signals reach a steady state. In preprocessing, the functional images were registered to the structural images of each participant for spatial alignment and registered to the base volume of the functional images for head motion correction. These time-series data were then spatially smoothed with a 5-mm full-width at half-maximum (FWHM) Gaussian kernel and normalized as a percent of the mean for conducting statistical analyses after the values of voxels outside the brain were excluded.

In individual analyses, each participant's preprocessed data were analyzed using a general linear model (GLM) with 8 regressors. Two regressors were for the time points that 30-s task blocks of the intrinsic motivation and non-intrinsic motivation conditions were initiated respectively. To partial out the effects of head motion artifacts, six regressors of head motion parameters were also considered. The GLM computed the hemodynamic responses of two regressors of interest (i.e., intrinsic motivation and non-intrinsic motivation memories) compared to the baseline state.

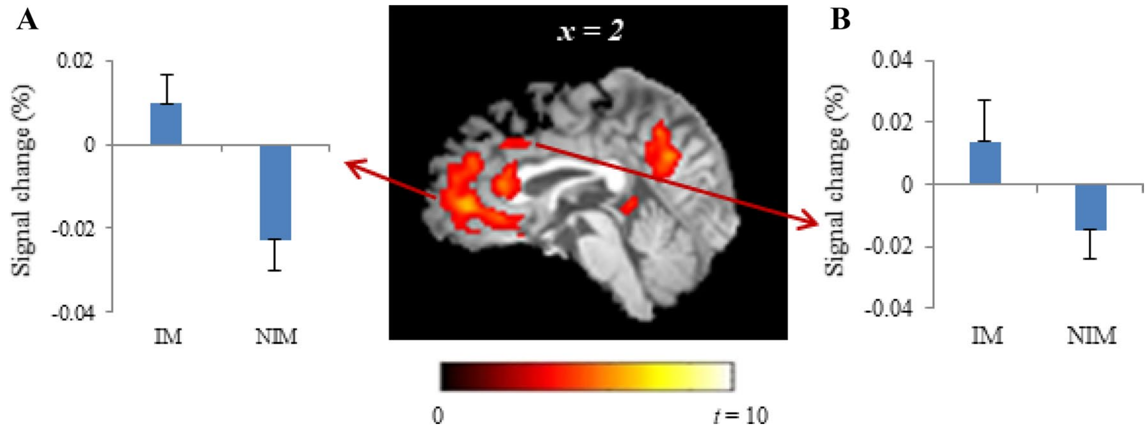

Fig. 2 The right ventromedial prefrontal cortex (**a**) and anterior cingulate cortex (**b**) were more activated during intrinsically-motivating memories than during non-intrinsically-motivating memories (corrected $p < 0.05$). BOLD signal changes between the two conditions are presented. *IM* intrinsic motivation memories, *NIM* non-intrinsic motivation memories

For group analyses, each participants' statistical data were normalized to the Montreal Neurological Institute (MNI) template using their standardized high-resolution structural images and were resampled to $2 \times 2 \times 2$ mm^3 voxels. Subtraction analyses were then conducted to identify the neural activations during intrinsic motivation memories vs. during non-intrinsic motivation memories. Matched-Pairs *t*-tests were used to examine the neural differences between the two conditions.

Psychophysiological interaction (PPI; Friston et al. 1997) analyses were also conducted to identify the neural interactions between the brain regions activated during intrinsic motivation memories. Among the brain regions activated in the subtraction analyses between the intrinsic motivation versus non-intrinsic motivation conditions, the brain regions known to be related to intrinsic motivation (i.e., ACC and VMPFC) were considered as the seed bran regions for the PPI analyses.

For these analyses, each participant's preprocessed data were first analyzed using another GLM additionally considering the regressors for the neural responses of the seed brain region and its neural interactions with each of the intrinsic motivation versus non-intrinsic motivation conditions. Participants' statistical data were also normalized to the Montreal Neurological Institute (MNI) template using their standardized high-resolution structural images and were resampled to $2 \times 2 \times 2$ mm^3 voxels. Then, the PPI analyses were performed to examine the neural interactions of the seed brain region with other brain regions in the intrinsic motivation condition compared to the non-intrinsic motivation condition.

For correcting multiple comparison inferences in the group-level subtraction and PPI analyses, Monte-Carlo simulation (Forman et al. 1995) was used, which determined the cluster-wise threshold (corrected $p < 0.05$) considering both the voxel-wise threshold ($p < 0.005$) and cluster size ($n \geq 54$, a minimum volume of 432 mm^3).[1] The brain regions significantly activated in the subtraction and PPI analyses were reported in MNI coordinates.

Results

We found that the right VMPFC (Fig. 2a), right ACC (Fig. 2b), bilateral dorsolateral prefrontal cortex, posterior cingulate cortex, and left middle temporal gyrus were more activated when participants remembered intrinsically-motivating memories than when they remembered non-intrinsically-motivating memories (corrected $p < 0.05$). No brain region was more activated when participants remembered non-intrinsically-motivating memories than when they remembered intrinsically-motivating memories. The results of the subtraction analysis appear in Table 2.

The right VMPFC (peak coordinates of the seed brain region: 2, 48, 0; volume: 19,672 mm^3) and right ACC (peak coordinates of the seed brain region: 2, 28, 32; volume: 520 mm^3), observed in the subtraction analysis, were considered as seed brain regions for PPI analyses. PPI analyses showed that neither brain seed regions interacted with the other three brain regions featured in Table 2. The two seed regions themselves, however, interacted with one another. Specifically, the right ACC as a seed showed greater negative interactions with the right VMPFC (peak MNI coordinate: 6,

[1] Using a conservative statistical threshold in neuroscience studies reduces Type I error rates but increases Type II error rates, which possibly simplifies psychological phenomena as publishing statistically large and obvious neural activities. To balance type I and type II error rates (Lieberman & Cunningham, 2009), we had decided to use a relatively liberal voxel-wise threshold.

Table 2 Results of the subtraction analysis between intrinsically-motivating and non-intrinsically-motivating memories

Brain region	BA	Volume	Side	MNI coordinates			Maximum *t* value
				x	y	z	
Intrinsically-motivating − Non-intrinsically-motivating memories							
Ventromedial prefrontal cortex	10	19,672	R	2	48	0	6.48
Anterior cingulate cortex	32	520	R	2	28	32	4.07
Dorsolateral prefrontal cortex	9	3232	L	−24	40	36	5.64
	8	3216	R	22	40	42	6.95
Posterior cingulate cortex	31	4176		0	−62	28	6.25
Middle temporal gyrus	21	448	L	−64	−2	−18	5.53

The cluster-wise threshold (correct $p<0.05$) is determined by voxel-wise threshold ($p<0.005$) and the minimum volume (54 contiguous voxels; 432 mm^3)

44, 10; maximum t value = 4.56; volume: 512 mm^3) when participants remembered intrinsically-motivating memories relative to when they remembered non-intrinsically-motivating memories (corrected $p<0.05$). As a seed, the entire volume of right VMPFC activity observed in the subtraction analysis did not show any interactions with any other brain regions. However, a supplemental PPI analysis using the small volume of right VMPFC activity as a seed (i.e., a sphere with a diameter of 5 mm centered around the peak coordinates) confirmed the negative interactions with right ACC activity (peak MNI coordinate: 2, 20, 32; maximum t value = 5.10; volume: 480 mm^3) when participants remembered intrinsically-motivating memories relative to when they remembered non-intrinsically-motivating memories (corrected $p<0.05$). Together, these PPI analyses revealed that the right ACC as a seed showed negative interactions with the right VMPFC, just as the right VMPFC as a seed showed negative interactions with the right ACC.

Discussion

In the present study, we sought to identify the neural correlates of retrospective intrinsic motivation memories. To do so, we compared the neural activations when participants remembered intrinsically-motivating situations vs. when they remembered non-intrinsically-motivating situations.

We found that the VMPFC showed greater neural activity in the memories of intrinsically-motivating situations than in the memories of non-intrinsically-motivating situations. The VMPFC, together with the striatum, is a well-known brain region for reward processing (Berridge and Kringelbach 2008; McClure et al. 2004). In particular, VMPFC activity is related to calculating and storing the values of rewarding stimuli or situations, providing the mental space where people compare the competing values in decision-making situations (O'Doherty 2004, 2007). Though the brain regions related to reward processing are known to mainly reflect the valuation of extrinsic rewards (Berridge and Kringelbach 2008; Rolls 2004), current studies have found that these brain regions reflect the valuation of intrinsic or social rewards as well (Di Domenico and Ryan 2017; Reeve and Lee 2019a). VMPFC activity of this study suggest the remembering of the pleasurable aspect of people's intrinsic motivation.

In addition, greater ACC activity was observed in the memories of intrinsically-motivating situations than in the memories of non-intrinsically-motivating situations. ACC activity has been observed in diverse cognitive processes and is known to have multiple functions (Bush et al. 2000). ACC activity is known to evaluate personal importance during a given situation (Heilbronner and Hayden 2016). In addition, the ACC, together with the DLPFC, importantly functions for the exertion of mental effort (Shackman et al. 2011). ACC activity is also activated while monitoring errors and conflicts as well as regulating emotional and cognitive processes in decision-making situations (Carter et al. 1998; Williams et al. 2004). In the present study, participants neither compared competing options nor monitored errors and conflicts during task performance. Rather, ACC activity of this study suggest the remembering high personal importance within the valued aspect of people's intrinsic motivation.

The crucial roles of pleasure (related to VMPFC activity) and personal meaning (related to ACC activity) in the memories of intrinsic motivation are in line with the theoretical position of SDT (Ryan and Deci 2017). SDT conceptualizes that intrinsic motivation is based on the pursuit and satisfaction of psychological needs (e.g., autonomy, competence, relatedness). Need pursuit and satisfaction encompass not only the hedonic aspect (e.g., positive emotional reactions) but also the eudaimonic aspect (e.g., meaning, flourishing, and the affordance of opportunities for autonomy, competence, and relatedness satisfactions) (Ryan and Deci 2017). Therefore, within the SDT framework, both hedonia and eudaimonia are considered as core parts in the construction and reconstruction of intrinsically-motivating memories (Ryan et al. 2013; Ryan and Huta 2009).

The neural activations during retrospective intrinsic motivation memories seem to be somewhat different from the neural activations that occur during the on-going experience of intrinsic motivation. In previous neuroimaging studies, when participants actually experienced intrinsic motivation during a task performance, they generally showed not only the neural activations of the cortical brain regions (e.g., ACC, VMPFC) but also those of the subcortical brain regions (e.g., striatum, anterior insula) (Lee and Reeve 2017; Leotti and Delgado 2011, 2014). In this study, however, subcortical neural activity was not observed when participants retrospectively remembered the intrinsic motivation episodes. We can assume that, though the on-going experiences of intrinsic motivation is experienced by the involvement of both cortical (conscious) and subcortical (unconscious) processes, it is stored in a conscious form in the cortical brain regions, and then represented and utilized when the information is needed. This is consistent with the neuroscience knowledge that many forms of emotional and motivation experiences processed by subcortical brain regions are stored in the cortical brain regions (Reeve and Lee 2019b). This is also consistent with the motivation theories that the accumulated experiences of affective motivation (e.g., interest) form a "consciously-rich emotional schema" (Reeve et al. 2015).

This idea is supported by the neural activation patterns observed in this study in terms of the processes of episodic memories. Not only the cortical brain regions (e.g., prefrontal and posterior parietal regions) but also the subcortical brain regions (e.g., hippocampus) are known as hub brain regions for the encoding and retrieval processes of episodic memories (Cabeza et al. 2008; Wagner et al. 2005). In this study, however, only the cortical brain regions including the dorsolateral prefrontal cortex and posterior cingulate cortex showed greater neural activations in the memories of intrinsically-motivating situations than in the memories of non-intrinsically-motivating situations. The cortical brain regions are associated with getting the gist from the details of episodic memories and reconstructing long-lasting memories based on this gist (Moscovitch et al. 2016). It seems likely that people can remember intrinsically-motivating episodes dominantly by retrieving the core features of these episodes rather than by retrieving the detail features. Therefore, these "gist-like" intrinsic motivation memories can be long-lasting and impactful on subsequent decisions and behaviors.

An interesting finding was that the neural activities of the VMPFC and ACC were complementary during intrinsic motivation memories. That is, the greater ACC activity that occurred during the memories of intrinsically-motivating situations, the weaker was the VMPFC activity that occurred. This same negative neural correlation between ACC and VMPFC activities has also been observed in decision-making studies (Walton et al. 2004). Not only neuroscientists (Rushworth et al. 2004) but also SDT researchers (Di Domenico and Ryan 2017) have suggested that VMPFC activity is more related to evaluating and representing the pleasurable values whereas ACC activity is more related to evaluating and representing the personal meaning. Therefore, we can assume that people can retrieve intrinsic motivation memories as more weighing the pleasurable aspect of the memories or the meaningful aspect. In other words, the experiences of intrinsic motivation are engraved and retrieved relatively more based on pleasure or personal meaning (Ryan and Deci 2017).

Limitations

The present study has possible limitations. First, the neural activations observed in the intrinsic motivation condition could be influenced not only by intrinsic motivation memories themselves but also by other confounding factors. Therefore, there could be possible alternative interpretations for the neural activations observed in this study. For example, intrinsically-motivating memories showed greater neural involvement as these memories could be more salient compared to the non-intrinsically-motivating memories. There might also be gender differences in the neural activations in the memories of intrinsically-motivating situations. Though we could not partial out all possible confounding effects, this study is worth noting as an exploratory neuroimaging study about retrospective intrinsic motivation memories, which suggest a possible neural explanation why intrinsically-motivating memories are memorable.

Second, though we explored the neural activations of the retrospective intrinsic motivation memories, we could not directly examine the influences of those neural activations on subsequent cognitive processes such as task persistence, decision-making, and so on. Because the memories of intrinsically-motivating situations are known to exert critical effects on people's cognition, emotion, and behavior, future research is required to test these subsequent effects.

Third, our memory-provoking questions encouraged participants to remember intrinsic motivation episodes in general (see Table 1), and we found that participants then showed all of the above: VMPFC activity, ACC activity, and VMPFC-ACC negative interactions. We therefore inferred that participants employed two complementary neural processes (one related to pleasure, the other related to personal meaning). To better understand these two complementary processes, a future research study could partition our one set of general intrinsic motivation memories into two conditions—one that asked participants to recall intrinsic motivation memories related specifically to pleasure (e.g., "remember an activity that you deeply enjoyed") and another that asked participants to recall intrinsic motivation memories related specifically to personal meaning (e.g., "remember an activity that was personally meaningful to you").

Fourth, though we recognized the two key aspects of intrinsic motivation memories, we could not fully understand the unique antecedents and consequences of these two different aspects. This neuroimaging study of people's memories of an intrinsically motivating episode in their life suggests that people store intrinsic motivation memories differently weighing two aspects—pleasure derived from earlier emotional experiences of need satisfactions on the one hand but personal meaning derived from earlier self-endorsement during need-satisfying opportunities on the other. Therefore, in future research, we need to understand why people could put different emphasis on their previous motivation memories and how these retrospective motivation memories might have different impacts.

Conclusion

In this study, we found that the pleasure-based reward processing in VMPFC activity and self-based processing in ACC activity are critical for the retrieval processes of intrinsic motivation memories. We also found that the relationship between the two neural functions was complementary. These neural findings suggest that intrinsically-motivating memories can be constructed and reconstructed by more emphasizing the aspect of intrinsic satisfaction stored as an experience of hedonic pleasure or the aspect of intrinsic satisfaction stored as an experience of personal meaning and the pursuit of eudaimonic purpose.

Compliance with ethical standards

Conflict of interest None of the authors on this paper has any conflict of interest to report.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki DECLARATION and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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