The Reconstruction of Choice Value in the Brain: A Look into the Size of Consideration Sets and Their Affective Consequences

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Abstract

■ It has been proposed that choice utility exhibits an inverted U-shape as a function of the number of options in the choice set. However, most researchers have so far only focused on the "physically extant" number of options in the set while disregarding the more important psychological factor, the "subjective" number of options worth considering to choose—that is, the size of the consideration set. To explore this previously ignored aspect, we examined how variations in the size of a consideration set can produce different affective consequences after making choices and investigated the underlying neural mechanism using fMRI. After rating their preferences for art posters, participants made a choice from a presented set and then reported on their level of satisfaction with their choice and the level of difficulty experienced in choosing it. Our behavioral results demonstrated that enlarged assortment set can lead to greater choice satisfaction only when increases in both consideration set size and preference contrast are involved. Moreover, choice difficulty is determined based on the size of an individual's consideration set rather than on the size of the assortment set, and it decreases linearly as a function of the level of contrast among alternatives. The neuroimaging analysis of choice-making revealed that subjective consideration set size was encoded in the striatum, the dACC, and the insula. In addition, the striatum also represented variations in choice satisfaction resulting from alterations in the size of consideration sets, whereas a common neural specificity for choice difficulty and consideration set size was shown in the dACC. These results have theoretical and practical importance in that it is one of the first studies investigating the influence of the psychological attributes of choice sets on the value-based decision-making process. ■

INTRODUCTION

We face a great number of choices in our daily lives. In the contemporary world, there are a stunning number of options, sometimes seeming almost infinite, to choose from in any single area; for example, from selecting vacation destinations to opting for particular insurance plans. Although classical economics and psychology had consensus that higher number of choice options is always better (Zuckerman, Porac, Lathin, Smith, & Deci, 1978; Langer & Rodin, 1976), recent empirical findings suggest a counterview: Having many options may not always leave individuals better off (Scheibehenne, Greifeneder, & Todd, 2010; Schwartz, 2004; Iyengar & Lepper, 2000). This adverse phenomenon has been shown in multiple ways, including decreases in choice satisfaction, choice motivation, and consumption rates in field study (Chernev, 2003a, 2003b; Iyengar & Lepper, 2000). On the basis of these previous studies, it has been proposed that positive affect arising from choice (i.e., choice satisfaction) draws an inverted U-shaped function as the number of alternatives increases because "benefits satiate and costs escalate" concomitantly with an increase in set size (Reutskaja & Hogarth, 2009; Coombs & Avrunin, 1977). This is primarily because an excessive number of alternatives produces cognitive overload resulted from excessive information searching cost and consequently increases choice difficulty. In this article, we label this phenomenon the "set size effect."

Taking a closer look at the set size effect, we can note that there are three components that are affected by any change in the size of an assortment set, and in effect, each of them might stimulate a positive change in affect: (1) set size: the physically extant number of options that one can choose from, (2) consideration set size: the psychologically perceived number of options that one would consider choosing from, (3) contrast: the relative distinctiveness of the chosen option compared with the other unchosen alternatives. Generally, enlarging the size of the assortment set leads to an increase in the size of the consideration set, but this is not always true (Scheibehenne et al., 2010; Hauser & Wernerfelt, 1990). For instance, if a larger set accompanies a larger consideration set, the contrast would expand only by a little, if at all. On the other hand, if there are no additional options attractive enough to be included in one's decision pool, the size of the consideration set will remain the same, but the contrast will be magnified to a greater extent. As explained above, these subfactors of the set size can alter and consequently affect

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choice experience in varying ways with varying magnitudes. However, little work has been done in attempting to disentangle the effect of these subcomponents from that of the set size per se. In this study, we conceptually distinguished between an increase in the size of the consideration set and an increase in contrast. On this basis, we constructed precise experimental conditions for investigating the separate contribution of each variable component: set size, consideration set size, and contrast.

Consideration Set Size

Most researchers have so far focused on the number of total options in a given set, which is arbitrarily configured by an experimenter. Little focus has been placed on the subjectively "perceived" number of options that an agent actually feels available. In real life, however, we rarely take all the provided options into account before making a decision. Suppose you wish to buy a T-shirt from an online store and you face more than 100 different T-shirts that you could choose from. In this case, you probably would not examine the details of every single available option and contemplate whether you are going to buy it or not. A number of past studies on human decision behavior have proposed that people undergo a "phased" decision process when they cope with this overwhelming situation: first, they filter all the available alternatives in a given set using relatively liberal criteria, and then, they undertake a detailed evaluation of the reduced set before finally selecting the best option (Bettman, Luce, & Payne, 1998; Shocker, Ben-Akiva, Boccara, & Nedungadi, 1991; Hauser & Wernerfelt, 1990; Wright & Barbour, 1977; Payne, 1976). Not only has it been established into computational dynamic search models in economics (Willemsen & Johnson, 2010; Jovanovic, 1979; McCall, 1970), empirical studies using eye-tracking technology have demonstrated the phased search and choice process (Reutskaja, Nagel, Camerer, & Rangel, 2011; Russo & Leclerc, 1994). Given these practical and empirical grounds, the number of screened options that remain after the subjective evaluation process, also known as the "consideration set size" in the field of marketing (Brown & Wildt, 1992; Roberts & Lattin, 1991; Shocker et al., 1991), would influence human choice behavior far more drastically than mere total number of extant options.

Contrast

Classical economic theory assumes that each alternative has a utility or subjective value, and consumers independently evaluate each option before they select the one with the highest value. Contrary to this common assumption (also known as value maximization theory), a number of studies have demonstrated that the preference for one option over the others can vary according to the context of the choice, that is, how a set of alternatives is composed (Hsee, 1998; Shafir, Simonson, & Tversky, 1993; Tversky & Shafir, 1992). Therefore, the set composition that we face can influence our choice behavior as well as our affective experiences during or after decision-making. In particular, when a less attractive option is added to the offered set along with a dominant option, making a choice gets easier by reducing choice conflict and thereby making the decision easier to justify (Shafir et al., 1993; Tversky & Shafir, 1992). Just as the same color seems brighter than it actually is when surrounded by darker colors (e.g., simultaneous brightness contrast illusion), the same option can appear as more attractive when it is presented alongside less attractive alternatives. This effect is termed the "contrast" effect. To expand the previous findings regarding the contrast effect in forced-choice contexts among multiple alternatives, our study employed parametrical differences in the degree of contrast across experimental conditions.

Neural Underpinnings of Choices among Multiple Alternatives

Putting together the well-established findings of these previous studies on the human decision-making process, it is clear that a choice among multiple alternatives first requires a screening of available options, which will delimit those that warrant further consideration, and then is followed by comparisons of the relative rewarding values associated with the various alternatives. According to previous neuroimaging studies, reward-based decision-making recruits the fronto-striatal circuit, which includes the medial pFC (mPFC), the dorsal ACC (dACC), the amygdala, and the striatum (Etkin, Egner, & Kalisch, 2011; Arana et al., 2003; Elliott, Newman, Longe, & Deakin, 2003; Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999). Specifically, the mPFC is considered to be involved in the comparison of hedonic values (e.g., reward) and to reflect the expected value (Blair et al., 2006; Arana et al., 2003; Elliott et al., 2003). The dACC, which has been associated with response conflict, is identified as representing the degree of competition among available response options (Marsh, Blair, Vythilingam, Busis, & Blair, 2007; Blair et al., 2006). Expanding from the study of Marsh et al. (2007), who operationalized the conflict severity with the total number of choice options, we manipulated the number of "considerable" options to directly examine the effect of the consideration set size in this study. Regarding the striatum, a large body of evidence has accrued with respect to its role in the valuation process when rewarding outcomes are presented, as well as in goal-directed behavior when incentive feedbacks are anticipated (Han, Huettel, Raposo, Adcock, & Dobbins, 2010; Knutson, Adams, Fong, & Hommer, 2001; Delgado, Nystrom, Fissell, Noll, & Fiez, 2000). Further studies have extended the view on the functional roles of the striatum and specifically in regards to the caudate nucleus, indicating its parametric responses to a rewarding value: from the degree of absolute monetary compensation, to "relative" monetary values, and even to the level of subjective affective arousal and preferences (Sharot, De Martino, & Dolan, 2009; Kuhnen & Knutson, 2005; Delgado, Locke, Stenger, & Fiez, 2003). We thus predicted that if the consideration set size is a more decisive factor for the subjective rewarding value (what is referred to as "choice utility"), then activation in the striatum would correlate with the consideration set size, rather than the set size per se.

We had two research goals in this article. First, we aimed to explore the set size effect in detail by separating the set size increase into three components (assortment set size, consideration set size, and contrast). We hypothesized that choice utility would be modulated by variations in consideration set size and contrast, but not just by assortment set size. Furthermore, we expected that consideration set size and contrast would have additive contributions to the choice utility. Hence, we predicted that increased positive affect would occur only when an increase in set size entails both enlarged consideration set size and higher contrast magnitude. To test our predictions, we examined whether the choice utility would be changed when (1) only the consideration set size is increased, (2) only the preference contrast is magnified, or (3) both the consideration set size and the level of contrast are increased. Second, we also sought to identify the neural mechanisms of such effects. More specifically, we wanted to locate the different brain regions responsible for representing the attributes of a set and for predicting the post-choice affective responses during decision-making. Therefore, we used both parametrical analyses and traditional general linear model (GLM) analyses to explore neural substrates where activity increased or decreased according to various choice set attributes and self-reported affective ratings.

METHODS

Participants

Twenty-seven (11 women) healthy participants (including 15 participants for the fMRI experiment) took part in the study for either course credit or payment ($10 per hour for the behavioral experiment only and $20 per hour for the fMRI experiment). Before the study commenced, informed written consent was obtained from the participants in a manner approved by the Institutional Review Board of Yonsei University. Before scanning, participants completed a screening form to declare any significant medical conditions they might have.

Experimental Tasks and Procedures

The present experiment consisted of five parts: (1) Pre-choice Preference task, (2) Consideration Set Size Decision task, (3) Choice task, (4) Post-Choice Evaluation task, and (5) Postexperimental task. The Postexperimental task was conducted only for fMRI participants after three scanning sessions (see Figure 1).

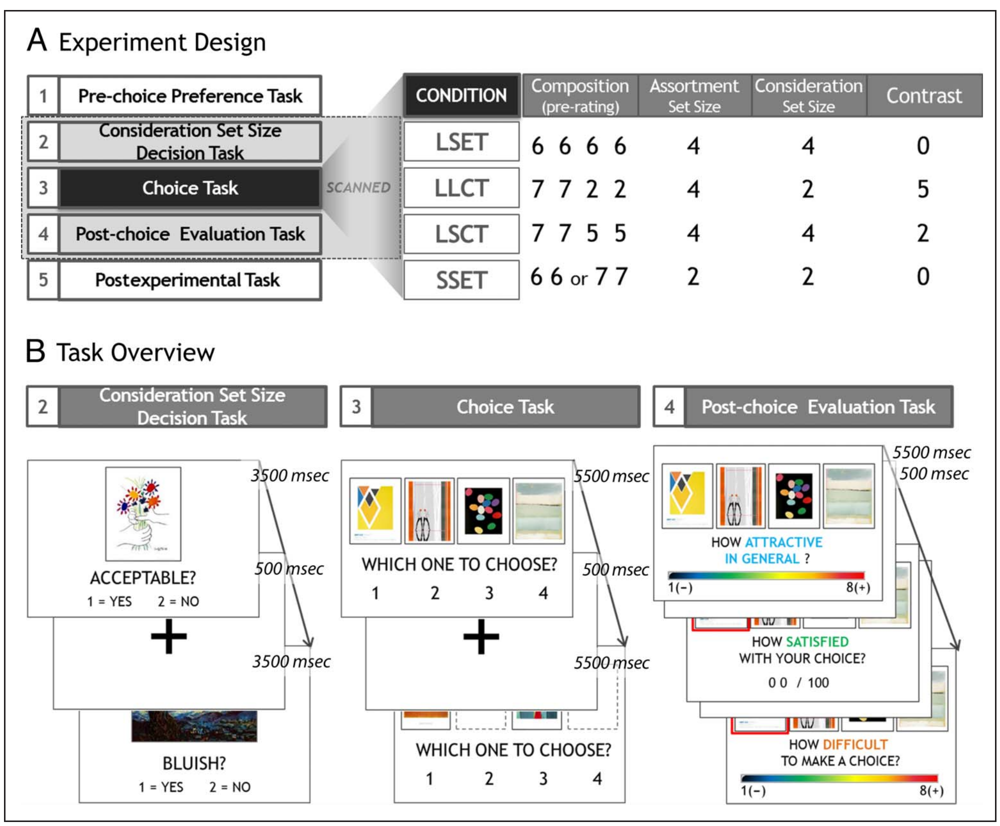

Figure 1. Experiment design and task overview. (A) Participants performed five behavioral tasks, among which the middle three tasks were scanned. The specific attributes of the four choice sets that were presented during the Choice task are detailed in the right panel. LSET = large set; LLCT = large set with large contrast; LSCT = large set with small contrast; SSET = small set. (B) During the consideration set size decision task, participants decided whether the presented stimulus was acceptable for inclusion in their consideration set. The perceptual decision-making task was conducted as an activation control. In the choice task participants chose the most preferable stimulus among the provided alternatives, and they then proceeded to the post-choice evaluation task, which requested that they report on (1) a set's overall attractiveness, (2) their choice satisfaction, and (3) the choice difficulty for each set.

A total of 340 art posters were obtained from the internet (www.allposters.com and www.art.com) and resized to 280 × 280 mm to control stimuli sizes. A pilot study with 14 healthy participants was conducted to verify that the stimuli used in the current experiment were not well known to general public. In this independent pilot study, participants rated familiarity of each art work using 4-point scale (1 = *never seen before*, 4 = *know very well*), and it confirmed that the stimuli were not familiar at all (mean = 1.29, *SD* = 0.25). To make decisions more salient, participants were asked to evaluate and select pictures as if they were choosing paintings to hang in their room. Before scanning, participants rated the subjective attractiveness of each art poster using an 8-point scale (1 = *very unattractive*, 8 = *very attractive*). Participants were able to change their preference rating until they felt satisfied and confident with their report. Once participants completed their ratings, they performed three decision-making tasks in the fMRI scanner. Among all the rated posters, 164 posters (3 stimuli for scores 1, 3, 4, and 8; 23 stimuli for scores 2 and 5; 53 stimuli for scores 6 and 7) were used in the following tasks. Posters for use were randomly selected when the reported number of stimuli exceeded the required number of stimuli for each score. All the tasks were programmed using the Cogent toolbox (www.vislab.ucl.ac.uk/Cogent) and MATLAB 7.8.0 (The MathWorks).

Before the main Choice task, the Consideration Set Size Decision task was conducted to check the subjective minimum attractiveness level to be included in each participant's consideration set. There were 24 trials for deciding individual consideration set size (three stimuli from each attractiveness score ranging from 1 to 8). Participants answered with either "Yes" or "No" to the question: "Is this picture good enough to be hung in your room?" A detailed explanation about the question was given in advance, telling them that they should answer "No" only if they could not bear for the presented stimuli to be hung in their rooms. On the basis of our independent pilot test results, 5-rated stimuli were included in individual consideration sets, when calculated by the midpoint of the average attractiveness rating of the pictures that were reported as acceptable and the average attractiveness rating of the pictures that were rejected (mean = 4.41, *SD* = 0.32). The procedure for the pilot test was the same as (1) the Pre-choice Preference task and (2) the Consideration Set Size Decision task. Therefore, we used an attractiveness rating of 5 as a consideration criterion point to configure the choice conditions in this experiment.

In the main Choice task, a set of pictures were presented on a screen, and participants were instructed to choose the picture that they prefer the most among the multiple alternatives in the set. On the basis of the results from the pilot test regarding an individual's consideration criterion, four different choice sets were configured varying in set size, consideration set size, and the level of contrast among alternatives. The four choice set conditions were (1) a small set (SSET) with two 6- or 7-rated items, (2) a larger consideration set (LSET) with four 6-rated items, (3) a large consideration set and a small contrast set (LSCT) with two 7-rated and two 5-rated items, and (4) a larger contrast set (LLCT) with two 7-rated and two 2-rated items (see Figure 1A). Compared with the SSET, which has a consideration set size of two items (each of which are rated equally), the LSET has doubled the consideration set size (to four options) with no increase in contrast among alternatives, which should entail that making choices becomes harder. The LSCT includes two 5-rated items, which enables relative comparison among items while constructing an enlarged consideration set size (of four items). The LLCT leads to a far more distinct comparison among items by having two additional unattractive items, but the consideration set size remains the same (two items). We conducted a post hoc independent study to verify reliability of condition manipulation in which rating 5 was used as a consideration criterion point. In the additional post hoc study, newly recruited 16 participants performed the same preference rating and choice tasks as the participants in the main experiment had performed. After the choice task, they were required to report the alternatives that they had considered when they made a choice in each choice set. Specifically, two questions were asked for each choice set: (1) Select all of the posters that you considered to make a choice. (2) Select all of the posters that you never considered to make a choice. This study confirmed that the consideration set sizes were significantly different across conditions in the same way that we predicted [consideration set size in LSET = LSCT, $t(15) = .19, p = .85$; LSET > LLCT, $t(15) = 3.02, p < .01$; LSCT > LLCT, $t(15) = 3.58, p < .01$]. The Choice task consisted of 40 trials with 10 trials for each of the four conditions. A set of pictures was displayed on the screen simultaneously and remained present for 5500 msec, with a preceding 500-msec fixation cross. The order in which the choice set condition was presented was pseudorandomized. Each picture appeared only once through the Choice task.

After the Choice task, participants were reminded which stimulus they had chosen among the alternatives, they then proceeded to the Post-choice Evaluation task. The picture sets used during the Choice task were presented again in a pseudorandomized order. For every choice set displayed, participants reported the perceived average attractiveness rating of choice set, choice satisfaction, and choice difficulty. The same 8-point scale was used for expressing average set values (1 = *very unattractive*, 8 = *very attractive*) and choice difficulty (1 = *not difficult at all*, 8 = *very difficult*). We used a 100-point scale for the choice satisfaction report. In the task, a red square appeared around the chosen picture while answering choice satisfaction and choice difficulty questions, but this square did not appear while answering the average set value question. Every question was presented for 5500 msec, with an additional 500-msec fixation cross.

Participants' ratings of the Post-choice Evaluation stage were our main dependent variables. This was because we aimed to explore the subjective affective consequences that emerged after a choice had been made.

Subsequent to the scanning sessions, participants rated the attractiveness of all the items that had been presented during the experiment using the same 8-point scale. This was conducted to monitor any changes in attitude after choice behaviors. However, the results will not be included here because it is beyond the scope of this article. Completing postexperimental questionnaires, participants were debriefed, thanked, and dismissed.

fMRI Data Acquisition and Data Analyses

The functional imaging was conducted on a 3-T Siemens MAGNETOM Trio MRI scanner. Functional data were acquired by using a gradient-echo planar pulse sequence (repetition time = 2000 msec, echo time = 30 msec, 3 × 3 × 4 mm resolution, 33 axial slices tilted 30° to the AC–PC plane, no gap, interleaved collection). High-resolution whole-brain T1-weighted anatomical scans (1 × 1 × 1 mm resolution, 192 axial slices) were also acquired. The first four volumes of each session were discarded to allow T1 equilibration effects. Stimuli were presented with MRI-compatible goggles, and responses were received with two MRI-compatible button boxes with four buttons each.

fMRI data were analyzed using SPM8 (Wellcome Department of Cognitive Neurology, London, UK). The slice acquisition timing was corrected by resampling all slices in time relative to the middle slice. Functional images were realigned to correct for head movement and coregistered with each participant's anatomical scan. After the segmentation of coregistered images, preprocessing further included the spatial normalization of the coregistered structural image to a Montreal Neurological Institute template provided in SPM8, and the spatial smoothing with an 8-mm FWHM isotropic Gaussian kernel. To minimize the effect of signal changes because of movements, we used the robust weighted least squares algorithm that weights each observation with the inverse of its variance (Diedrichsen & Shadmehr, 2005). Each scanning session was rescaled such that the mean global signal was 100 across the volumes. For the analyses, the volumes were treated as a temporally correlated time series and modeled by convolving a canonical hemodynamic response function and its temporal derivative with a delta function marking the onset of each trial. The resulting hemodynamic functions were used as covariates in a GLM along with a basis set of cosine functions that were used to high-pass filter the data and a covariate representing session effects. Least squares parameter estimates of the best-fitting synthetic hemodynamic response function for each condition of interest (averaged across scans) were used in pairwise contrasts and stored as a separate image for each participant. These different images were then tested against the null hypothesis of no difference between contrast conditions using one-tailed t tests. The data were statistically analyzed by treating participants as a random effect at the group level.

All the GLMs treated each trial as an event with 0 duration. Analyses focused on the imaging scans during the Choice task. We modeled separate GLMs with each modulator regressor to parcel out each modulatory effect during choices. GLM 1 to 3 were intended to identify the regions whose activity was positively related with subjective responses using parametric analyses. Therefore, the model contained regressors for all the choice-making trials, fixation trials as a baseline condition, as well as set composition attributes or affective responses after choice (GLM 1: consideration set size, GLM 2: choice satisfaction, GLM 3: choice difficulty) as a coregressor of interest for each choice-making trial. Parameter estimates for choice behaviors were estimated based on a participant's stated responses during the Consideration Set Size Decision task or the Post-choice Evaluation task. In particular, a parametric modulation analysis to explore the neural substrates representing subjective consideration set size utilized the individual data from the Consideration Set Size Decision task. Assortment set size was included in this model as an additional regressor to control the effect of the number of alternatives in a given choice set. Thus, the model had four regressors: (1) each picture set stimulus onset, (2) the participant's consideration set size for each picture set as Parametric Modulator 1, (3) the number of pictures in a set as Parametric Modulator 2, (4) fixation onset. In GLM 4 imaging data were modeled to the onset of the picture set presentation to broadly compare the brain activity according to the four different types of choice set conditions: LSET, LSCT, LLCT, and SSET. Additional parametric modulation analyses were performed based on GLM 4 using average attractiveness, choice satisfaction, or choice difficulty as a regressor of interest for each of the four conditions of a choice set. Unless stated otherwise, statistics were corrected for multiple comparisons using a combined p value/cluster size threshold of $p < .005/18$ voxels, which corresponded to an alpha level of $p < .05$ for the whole brain mask based on Monte Carlo simulation (Slotnick, Moo, Segal, & Hart, 2003).

RESULTS

We are going to focus on the results regarding choice satisfaction and choice difficulty here, as these are the two major affective consequences that have been typically focused on and measured in previous studies.

Behavioral Results

We performed a behavioral experiment first and then conducted an fMRI experiment to validate the behavioral experiment's results as well as to explore the underlying neural mechanisms that operate during choice-making among multiple alternatives. The general result pattern

Table 1. Differences in Behavioral Responses between Conditions

Assortment Set	*Large*			*Small*
Set Conditions	*LSET*	*LLCT*	*LSCT*	*SSET*
Choice satisfaction	69.16 (11.27)	71.52 (9.00)	73.21 (9.40)	66.83 (13.10)
Choice difficulty	5.02 (0.63)	3.74 (1.00)	4.44 (1.31)	4.29 (1.32)

Values in parentheses indicate standard deviations.

from the behavioral experiment remained the same when additional behavioral data from the fMRI experiment were included in the analysis. Therefore, the behavioral results from both the behavioral experiment and the fMRI experiment are collapsed here.

We first evaluated the choice satisfaction rating reported after the choice task. A repeated-measures ANOVA yielded a marginally significant main effect, $F(3, 24) = 2.59$, $p = .06$. However, results of polynomial trend analysis indicated a significant quadratic effect ($p < .05$) across conditions, indicating a nonlinear effect (e.g., an inverted U-shaped function) of the consideration set size. A priori t tests in which we were more interested confirmed a significant pairwise difference in choice satisfaction ratings, such that LSCT condition, the only condition that accompanied increases both in consideration set size and contrast with enlargement of the set size, elicited greater choice satisfaction compared with SSET condition. Specifically, the choice satisfactions of LSCT and SSET were significantly different, $t(26) = 2.35$, $p < .05$, whereas none of the other conditions with an enlarged assortment set size (LSET, LLCT) showed any difference from SSET (see Table 1 and Figure 2). This suggests that increased set size does not necessarily lead to greater choice satisfaction. LSET and LLCT (which only had enlarged consideration set size and increased level of contrast, respectively) did not show any effect on satisfaction at all, although both conditions had been enlarged in the assortment set size compared with SSET. In addition, although not predicted, pairwise comparisons found that the reported satisfaction of LSCT was significantly higher than that of LSET, $t(26) = 2.44$, $p < .05$. The significant satisfaction difference between LSCT and LSET indirectly shows the importance of a contrast effect because all the choice set attributes of interest (assortment set size, consideration set size, and contrast) except for the contrast effect, were the same in both conditions. These results are consistent with our hypothesis that changes of choice satisfaction driven by set size increase would be in effect only when there are increases both in the consideration set size and in the contrast level among alternatives.

Another repeated-measures ANOVA, which was carried out on the choice difficulty, revealed that choice set conditions have a significant effect, $F(3, 24) = 7.39$, $p < .001$. A trend analysis confirmed a significant linear decrease in choice difficulty as a function of contrast level ($p < .001$). Paired comparisons revealed significantly higher choice difficulty ratings only in LSET condition, which involved enlarged consideration set size without any contrast effect, compared with SSET condition (LSET vs. SSET, $t(26) = 2.71$, $p < .05$). Additional pairwise comparisons among large sets identified that making choices in LSET condition was significantly more difficult than in any other conditions (LSET vs. LSCT, $t(26) = 2.32$, $p < .05$; LSET vs. LLCT, $t(26) = 6.23$, $p < .001$). Also, it was notable to point out that experienced choice difficulty was allayed, compared with SSET, when the preference contrast became discernible by adding two less preferred options although the total set size was rather increased (LLCT vs. SSET, $t(26) = 2.33$, $p < .05$). Choice difficulty was not different when the collapsed condition of a large assortment set size (LSET, LSCT, and LLCT) was compared with SSET, $t(26) = 0.10$, $p = .92$. However, when the choice set conditions of a large consideration set (LSET and LSCT), not the assortment set size, were compared with those of a small consideration set (LLCT and SSET), it was notable that the difference in choice difficulty reached a statistically significant level, $t(26) = 4.05$, $p < .001$. Thus, it can be suggested that choice difficulty is largely influenced by the size of consideration set rather than by that

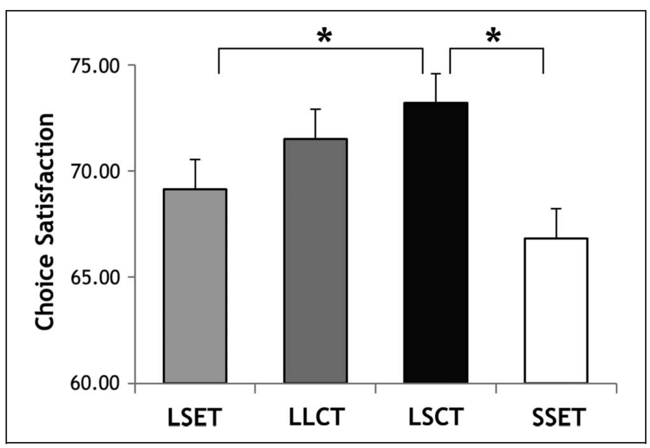

Figure 2. Behavioral results. The choice satisfaction of LSCT (large set with small contrast) was significantly higher than that of SSET (small set), $t(26) = 2.35$, $p < .05$, whereas none of the other conditions with an enlarged assortment set size (LSET = large set; LLCT = large set with large contrast) showed any difference from SSET. Also, there was a significant difference in the choice satisfaction between LSET and LSCT condition, $t(26) = 2.44$, $p < .05$. Error bars indicate *SEM*.

Table 2. Parametric Modulation Analyses

Regions	*Lat.*	*BA*	*Talairach Coordinates* *x*	*y*	*z*	*z Score*
1. Total Assortment Set Size						
Inferior frontal gyrus	L	9	−44	7	27	3.50
	R	9	42	13	30	2.01
Fusiform gyrus	L	37	−40	−53	−14	3.34
Lingual gyrus	L	18	−10	−76	−5	3.99
	R	18	10	−76	−3	3.85
Inferior occipital gyrus	R	18	42	−82	−6	3.25
Middle occipital gyrus	R	18	26	−93	11	3.19
2. Consideration Set Size						
Caudate nucleus[a]	L	N/A	−8	15	−2	3.13
Dorsal cingulate gyrus	L	32	−4	19	39	3.27
	R	32	4	16	41	3.82
Insula	L	47	−36	29	0	3.50
	R	13	42	16	8	3.47
Parahippocampal/fusiform gyrus	L	19	−32	−43	−1	3.31
	R	19	34	−43	−3	3.41
Medial frontal gyrus	R	6	14	4	50	3.22
Superior frontal gyrus	N/A	6	0	12	50	4.16
Precentral gyrus	L	6	−46	−2	37	3.35
Lingual gyrus	N/A	18	0	−85	1	3.98
Cuneus	L	18	−2	−92	18	3.89
3. Overall Set Value						
Medial orbitofrontal gyrus	R	25	8	26	−16	3.49
Lateral orbitofrontal gyrus	R	11	38	46	−47	4.11
Inferior frontal gyrus	L	46	−53	33	7	3.32
	R	45	57	20	19	3.03
Inferior parietal lobule	R	39	44	−66	39	3.38
4. Choice Satisfaction						
Ventro medial frontal gyrus	R	10	6	5	−8	3.14
Anterior cingulate gyrus	R	32	8	39	1	3.09
Inferior parietal lobule	L	40	−40	−43	39	3.75
	R	40	55	−31	40	3.20
Precuneus/superior occipital gyrus	L	19	−36	−78	33	3.31
	R	19	38	−74	36	3.50

Table 2. (*continued*)

Regions	*Lat.*	*BA*	*Talairach Coordinates* *x*	*y*	*z*	*z Score*
5. Choice Difficulty						
Insula	L	13	−34	17	−1	3.10
	R	13	30	24	6	4.91
Dorsal cingulate gyrus	L	9/32	−10	25	27	3.60
Lingual gyrus	R	18	18	−82	−1	3.22
Middle occipital gyrus	L	19	−38	−78	1	2.83
6. Choice Satisfaction: LSCT versus SSET						
Caudate nucleus[a]	L	N/A	−6	11	−6	3.57
	R		2	16	−1	3.28
Ventromedial prefrontal gyrus	L	10	−10	52	−8	3.38
7. Choice Satisfaction: LSCT versus LLCT						
Caudate nucleus[a]	L	N/A	−6	11	−9	3.88

Lat. = laterality; BA = approximate Brodmann's locations.

[a]Activated regions are globally overlapped.

of total set and decreases linearly as a function of preference contrast among alternatives even when the total set size remains the same.

fMRI Results

Exploratory Parametric Analyses

Brain regions reflecting total assortment set size. We first contrasted a large choice set condition, the collapsed condition that three conditions with four choice alternatives (LSET + LSCT + LLCT) are combined with a small choice set condition (SSET). This contrast was meant to identify neural regions encoding the actual size of the presented choice set. Significant activations were seen in the occipital cortex, the bilateral inferior frontal gyrus, and the dACC. However, when the effect of consideration set size was removed in a parametric modulation model (see GLM 1 in Methods), the activation was restricted only to the bilateral inferior frontal gyrus and the occipital cortex.

Brain regions reflecting subjective consideration set size. We next sought to investigate areas that encode the size of subjective consideration sets for each presented set by exploring brain regions that increase and decrease their activities as the number of consideration sets varies. We conducted a parametric modulation analysis using each participant's consideration set size (the self-reported data obtained from the Consideration Set Size Decision task) as parameters. The result revealed that there were several regions, including the left caudate nucleus, the bilateral insula, the dACC, and the bilateral parahippocampal gyrus extending to the fusiform gyrus whose activity was parametrically modulated by the participants' consideration set sizes (see Table 2 and Figure 3). It is important to note that the brain activities in those regions were occurred when the effect of the assortment set size was regressed out in the model (see GLM 1 in Methods). It can be argued that the current neural activation could be simply because of overall value of a choice set, rather than the subjective consideration set size. However, another parametric modulation analysis using overall attractiveness ratings of a choice set as trial-by-trial parameters revealed no overlapping activation in the previously identified regions—striatum, dACC, and insula. Instead, we found stronger activations in the medial OFC/rectus, the right lateral OFC, and the left inferior frontal gyrus, as a participant's reporting of overall value for a choice set increases (see Table 2). Thus, the results suggest that the aforementioned brain regions track the changes of the perceived set size that the participants "would" choose from, neither the total set size that they "could" choose from nor the overall value of the presented set.

Brain regions predicting choice satisfaction and choice difficulty. We also examined specific brain regions that

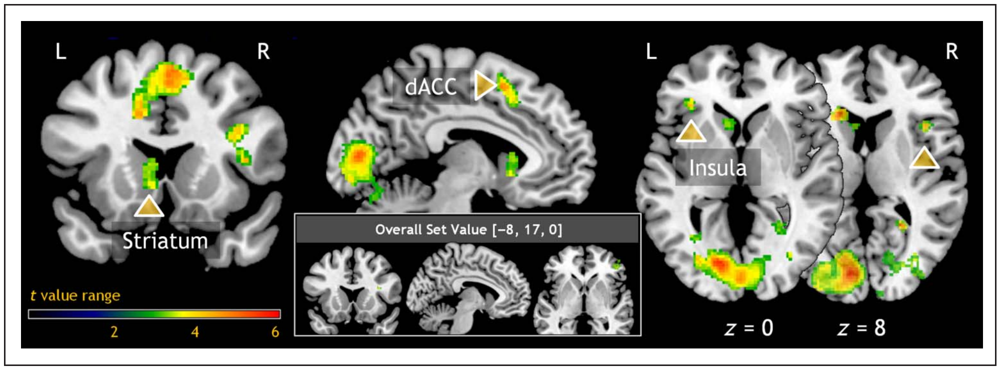

Figure 3. Neural representations of subjective consideration set size. A parametric modulation analysis revealed that the left caudate nucleus, the dACC, and the left anterior insula were parametrically modulated by the size of subjective consideration sets, independent from the size of the physical assortment set. Another parametric modulation analysis using overall set value as parameters demonstrated no overlapping activation. Activation maps on the same coordinate [−8, 17, 0] as above are shown in the box. Effects were significant at $p < .05$ (corrected).

reflect individual behavioral responses, especially the participants' choice satisfaction ratings as obtained during the Post-choice Evaluation task. The analysis identified ventral mPFC (vmPFC; see Table 2 and Figure 4A), indicating that the level of neural activation in the vmPFC during decision-making predicts how much one would be satisfied with his or her choice later. Additionally, in tracking where the reported degree of choice difficulty is processed, we discovered that the dACC and the bilateral insula were major representative regions (see Table 2 and Figure 4B). These results illustrate that when participants found it more difficult to choose a single item among the given set, higher neural activity was observed in the dACC and insula.

Consideration Set Size and Its Affective Consequences: Striatum and dACC

The striatum's role in registering choice satisfaction resulting from variations in the consideration set size. The role of the striatum in reward processing has been well documented, especially in its tracking of expected hedonic consequences (Sharot et al., 2009).We thus expected that the "postreported" choice satisfaction because of the enlarged number of considerable options would be reflected in the striatum activity in LSCT, which was our primary focus condition with both large consideration set size and a moderate level of contrast among alternatives. We performed whole-brain analyses and parametric modulation analyses on choice satisfaction under different set conditions. First, we compared LSCT with two other conditions that have smaller consideration sets (SSET and LLCT). From the contrast of LSCT versus SSET, activations in several regions including the left lateral OFC, the right insula, the dACC, and the left caudate nucleus were found (see Table 3). Additionally, we performed a pairwise comparison of LSCT versus LLCT, which had the same assortment set size of four items, but different consideration set sizes. The contrast between LSCT and LLCT revealed that significant activity

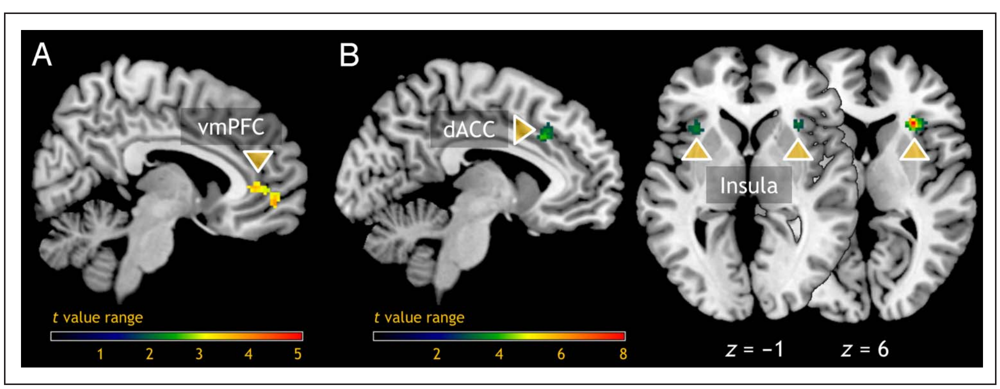

Figure 4. Neural substrates tracking choice satisfaction and choice difficulty. (A) According to the parametric modulation analysis of choice satisfaction, the activation magnitude in the vmPFC when making a choice could predict the level of satisfaction from the choice. (B) Another parametric modulation analysis identified that the left insula and the dACC represented the level of choice difficulty that participants were experiencing during decision-making. The effects of both A and B were significant, $p < .05$, corrected. See Table 2 for coordinate information.

was present in the right lateral OFC, the right putamen, and the left caudate nucleus. These two main contrasts revealed that greater activity was commonly present in the caudate nucleus (x, y, z = −12, 19, −3) and importantly, the region overlapped with the activation peak voxel that was identified from the former parametric modulation analysis reflecting the consideration set size (see Tables 2 and 3).

Table 3. Whole-brain Analyses

			Talairach Coordinates			
Regions	*Lat.*	*BA*	*x*	*y*	*z*	*z Score*
LSCT versus SSET						
Caudate nucleus[a]	L	N/A	−12	19	−3	3.54
Insula	R	13	42	18	8	3.49
Dorsal cingulate gyrus	L	32	−2	14	43	3.20
	L	32	−6	17	36	3.07
	L	32	−2	29	32	2.78
Parahippocampal gyrus	R	19	30	−45	−6	3.58
Lateral orbitofontal gyrus	L	11	−18	46	−16	4.24
Thalamus	R	N/A	20	−29	1	2.83
Lingual gyrus	R	18	8	−76	−5	4.35
Cuneus	N/A	18	0	−89	6	4.06
LSCT versus LLCT						
Caudate nucleus	L	N/A	−12	19	−4	3.85
	R	N/A	10	8	−4	3.55
Putamen	R	N/A	16	12	3	3.15
	R	N/A	20	7	−10	3.04
Dorsal cingulate gyrus	R	32	4	17	36	3.24
Lateral orbitofrontal gyrus	R	11	32	48	−12	3.57
Inferior parietal lobule	R	40	59	−27	37	3.81
Dorsomedial prefrontal gyrus	L	8	−6	24	44	3.65
	R	8	2	26	51	2.70
Amgydala/pararhippocampal gyrus	L	34	−20	3	−14	3.53
Cuneus	N/A	18	0	−89	8	3.11
Superior occipital gyrus	R	19	34	−84	24	3.14
LSET versus SSET						
Dorsal cingulate gyrus	L	32	−12	21	32	2.96
Parahippocampal/fusiform gyrus	R	19	34	−45	−3	3.09
Lingual gyrus	R	18	12	−74	−1	3.57
Cuneus	R	18	6	−92	16	2.55
LSET versus LLCT (.001/No Extent)						
Dorsal cingulate gyrus	L	32	−12	19	32	3.21

Lat. = laterality; BA = approximate Brodmann's locations.

We next examined whether the degree of parametric modulation in the striatum's tracking of choice satisfaction was altered by the size of the consideration set. We specifically compared LSCT condition with other conditions because we sought to examine brain regions representing higher choice satisfaction caused by the two contributors: enlarged consideration set and higher contrast magnitude. In other words, we sought to detect the neural substrates in which variations in choice satisfaction was more clearly represented in the condition that manifests larger consideration set size with a moderate level of contrast (LSCT) compared with other conditions that have smaller consideration set size with two extremes of contrast (SSET and LLCT). Results showed that the striatum encoded individual choice satisfaction with greater sensitivity under LSCT conditions than under SSET and LLCT conditions. The activation in the ventral part of the caudate nucleus here is particularly important because it is largely overlapped with the striatum region that was identified as parametrically changing according to the size of the individual consideration set in the former analysis.

Common systems representing positive affective consequences resulting from increases in the consideration size. On the basis of the overlapping results of these parametric modulation analyses and whole-brain amplitude analyses, we next sought to explore the common neural substrates tracking changes of the consideration set size and choice satisfaction resulted from an increase in the consideration set size. We thus instigated a formal conjunction analysis between the following imaging results: (1) a parametric modulation of consideration set size, (2) a contrast between LSCT versus SSET, and (3) a parametric modulation of choice satisfaction in the contrast between LSCT versus SSET. This was done to locate the brain regions involved in reflecting both the size of a consideration set and the level of individual choice satisfaction. The LSCT versus SSET contrast was chosen for the following two reasons: (1) LSCT entails increases in both consideration set size and in the degree of contrast at the same time, the only condition that an increase in choice utility was expected in our hypotheses; (2) LSCT versus SSET showed significant differences in choice satisfaction from the behavioral study. From this conjunction, activation was restricted only to the bilateral caudate nucleus (Figure 5A). Exactly the same region was identified when a contrast map of LSCT versus LLCT (in which the physical size of a set was controlled) was used instead of LSCT versus SSET. This was true even when, a parametric modulation map of LSCT versus LLCT, as a substitution for LSCT versus SSET, was used for the conjunction. This finding suggests that, when making choices, the overlapping region of the caudate nucleus is hired to encode the expected satisfaction with a change of the consideration set size.

The dACC's involvement in tracking choice difficulty resulting from variations in the consideration set size. Additionally, we next examined neural predictors for choice difficulty during choices involving large consideration sets. We first contrasted expression patterns for the most difficult condition with a large consideration set (LSET) versus two other conditions with smaller consideration sets (SSET and LLCT). These contrasts were meant to show the effect of psychological difficulty in the choices among larger consideration sets. When LSET and SSET conditions were compared, significant activation was seen only in the dACC. The same region of dACC was also found in the contrast map of LSET versus LLCT ($p < .001$, no extent voxel threshold).

Common systems representing negative affective consequences resulting from increases in the consideration size. Because we found the common activation in the dACC from our previous parametric modulation analyses, a conjunction map was constructed to explore the shared neural circuit that represents changes of the consideration set size and choice difficulty caused by an increase in the consideration set size. We conducted a triple conjunction analysis consisting of (1) a parametric modulation of consideration set size, (2) a contrast between LSET versus SSET, and (3) a parametric modulation of choice difficulty. We used the contrast of LSET versus SSET here because it

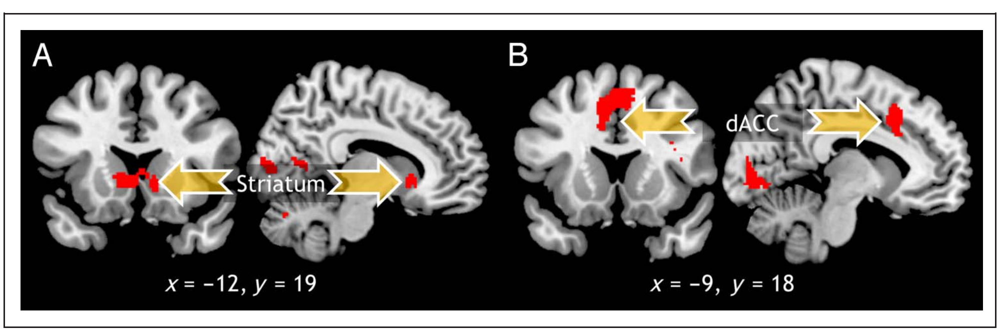

Figure 5. Shared neural representations for tracking consideration set size and post-choice behavioral responses. (A) Choice satisfaction. The right caudate nucleus was identified as a common brain area from the triple conjunction of a parametric modulation map of consideration set size, a contrast map between LCSCT versus SSET, and a parametric modulation map of choice satisfaction in the contrast between LCSCT versus SSET. (B) Choice difficulty. dACC was revealed as a common brain area from the triple conjunction of a parametric modulation map of consideration set size, a parametric modulation map of choice difficulty, and a contrast map between LCS versus SSET. Each with uncorrected p value threshold of .05, no extent voxels for each contrast, $.05 \times .05 \times .05$.

embodies a psychological conflict caused by doubling the size of a consideration set but without inducing the contrast effect among the alternatives. The analysis observed common neural activation in the dACC (Figure 5B). To illustrate the effect of an increase in the consideration set size while the total set size remains the same, another conjunction analysis was performed using LSET versus LLCT (instead of LSET vs. SSET). From this conjunction, we again discovered significant common activation in the same area.

DISCUSSION

The current study provides novel insights into how certain underlying psychological attributes of a choice set can shape human decision-making processes and affective consequences that result after choices have been made. As the number of options available for a choice increases, the size of one's subjective consideration set and the level of contrast experienced among the options would either be enlarged or not, depending on how the increased choice set is constructed. Our behavioral results demonstrated that both larger consideration set and greater contrast are required for higher choice satisfaction. In other words, an increase in the available options that only involves an increase in the size of the consideration set or in the level of contrast alone is not likely to lead to higher choice satisfaction. In addition, it was also revealed that choice conflict is increased when the number of options to be actually considered is enlarged, whereas an increase in set size per se does not affect choice difficulty at all. Therefore, these results suggest the possibility that the set size effect drawing an inverted U-shaped function would be actually driven by changes in consideration set size—even when total assortment set size remains the same.

Beyond the empirical behavioral findings, we also examined the neural mechanisms associated with choice making among multiple alternatives. Of particular importance was the fact that, when the size of one's subjective consideration set increases, neural specificity in the striatum (caudate nucleus) and the dACC was observed with respect to two key variables: choice satisfaction and choice difficulty. An increase in the size of subjective consideration sets, independent from any increase in the total size of the choice set, was strongly associated with increased BOLD signals in the striatum, dACC, and insula. Among these regions, the same voxels in the striatum, but not those in the dACC, were identified as reflecting the increased subjective choice satisfaction as a function of consideration set size. In contrast, the degree of difficulty during choice was represented in dACC but did not have any association with striatum.

The present results support and further expand upon previous findings about functional specificity in the striatum and dACC. In the study of Marsh et al. (2007), BOLD activation in the caudate head and dACC were positively associated with an increase in the number of decision options. The concept of "the number of options" in their study was more comparable to "the size of the consideration set" in our study, rather than to the total set size. The participants in Marsh et al. (2007) had to select one stimulus with highest reward value (a value that had been learned during a preceding learning phase), which means that they had to retrieve and compare all the stimuli's objective values, thus open up all the options for consideration. Therefore, their findings are in line with ours in showing that parametric alterations in the caudate nucleus and dACC occur in response to changes to the size of the consideration set, not with the actual size of the set itself. Interestingly, in another fMRI study by Reutskaja (2008), those brain regions were also identified as following a quadratic function, not a linear function, in response to the total number of presented options. These results were consistent with behavioral findings on the set size effect or choice overload phenomenon. Because their research primarily focused on the number of choice options, the activity associated with the total set size cannot be dissociated from the activity correlated with the consideration set size. Nonetheless, it is worth noting that the brain regions reported in Reutskaja (2008) were consistent with those identified in the current experiment as reflecting the size of one's consideration set, independent from the size of total choice options.

Besides the neural representations for consideration set size, the current data suggest that the striatum and dACC have dissociated roles for representing choice satisfaction and choice difficulty, respectively. A large and ever-growing number of neuroimaging studies have consistently demonstrated the common neural structures that are involved in reward processing and goal-directed behavior, for example, the striatum, vmPFC, and OFC. These regions comprise a "ventral valuation network" (Montague, King-Casas, & Cohen, 2006). Among the components of the ventral valuation network, the striatum is known to be particularly sensitive to rewards that are updated or changed over time and that accompany instrumental activities such as making a choice or learning, whereas the vmPFC responds to the receipt of subjectively rewarding values (Fehr, Fischbacher, & Kosfeld, 2005; Kuhnen & Knutson, 2005; Tricomi, Delgado, & Fiez, 2004; Delgado et al., 2003; Elliott et al., 2003; Knutson, Fong, Adams, Varner, & Hommer, 2001). Our results, as detailed in this article, are consistent with the existing literature: the BOLD signals in the vmPFC during choice-making scaled linearly with choice satisfaction. These results suggest that, during decision-making procedures, brain activity in the vmPFC can predict post-decisional affective rewarding values (i.e., choice satisfaction). In addition, when differences in the size of the consideration set were taken into account, amplified activation was identified only in the striatum, especially in the ventral part of caudate. Recent studies focusing on the striatum's role regarding action–outcome contingency indicated that the caudate nucleus is selectively activated when participants believed they were active agents responsible for the positive outcomes (Camille et al., 2010; O'Doherty et al., 2004; Tricomi et al., 2004; Schultz, Tremblay, & Hollerman, 2000). When considering those findings, it is important to note that the caudate nucleus was responsible in tracking choice satisfaction as a function of the consideration set size in this study. This implies that making choices among multiple alternatives might involve a proactive reconstruction process of choice sets, and such process operates trial by trial based on the subjective preferences of the individual.

The involvement of ACC in conflict monitoring has been extensively examined before. Most studies, however, have used perceptual decision-making tasks, which require different motor response selections based on perceptual judgments, such as the flanker task and the Stroop task (Kerns et al., 2004; Bush, Luu, & Posner, 2000). As a result, there is considerable controversy over the role of ACC in conflict monitoring, whether it represents only the response conflicts among competing actions or whether its role extends to higher-level decision conflicts among alternatives with similar subjective values. In our experiment, we found greater dACC activation when participants had to make choices among a large number of options to consider, compared with a small number of genuinely attractive options. Moreover, the same region was identified to parametrically reflect the subjective experience of choice difficulty, which indicates decisional conflict during choices. These results support other recent studies demonstrating ACC's role associated with a higher level of decision conflict in both cognitive and affective ways: for instance, facing unfair economic offers, choosing between two equally attractive options, and making difficult decisions that require the violation of moral beliefs (Pochon, Riis, Sanfey, Nystrom, & Cohen, 2008; Greene, Nystrom, Engell, Darley, & Cohen, 2004; Sanfey, Rilling, & Aronson, 2003; Shackman et al., 2011). In particular, our study supports and further expands the results of Pochon et al. (2008), who demonstrated that the dACC reflects decision conflict between similar preferences at the decision-making stage, even when a task was not associated with specific motion selection and preparation.

Among possible limitations of our study, one is that the examined choice sets are relatively small and have few variations, having either two or four options for selection. However, our main research objective was to demonstrate the influences of subjective attributes of a choice set (i.e., consideration set size and preference contrast), not of objective attributes (i.e., total set size), on affective consequences after decision-making. To directly manipulate the above-mentioned subjective attributes, experimental conditions were constructed based on participants' preference ratings, although the total set size could be somewhat limited. Furthermore, a large number of options would cause time pressure, which could be considered a very important research topic in decision science but not a main interest of this study. Therefore, we restricted the size of the choice set to four and compared the consideration sets comprising four options with those comprising only two options. However, it is also true that there could be potential confounding factors, such as the summed preference ratings of a choice set, because of the limited number of conditions and set size restriction. With the fixed number of alternatives in a choice set, a large consideration set size is highly correlated with total preference ratings. This suggests that the total preference ratings, not just the consideration set size, potentially affected the affective consequences regarding choices. Although these two concepts are closely intertwined with each other, it might be possible to disentangle the effect of these two, respectively, if conditions with more diverse total set sizes are examined. We believe future studies with more than three variations of consideration set would be better able to show the neural structures tracking the consideration set size and thereby strengthen our results. Additionally, although the current study focused on the effect of consideration set size and contrast while the total set size remains the same, future works could examine the effect of those in various sizes of candidate pool to elucidate the inverted U-shaped set size effect, which might be driven more by the consideration set size than the total assortment set size or the total preference ratings.

Another issue can be raised with respect to subjective value on which one's consideration set construction is based: whether the value remains consistent regardless of how choice alternatives are presented (e.g., presented independently, presented with other alternatives with different subjective preferences). In the current experiment, there is a limitation to clearly demonstrate any changes in the perceived attractiveness of choice options when they are presented in a cluster. However, our behavioral results on overall set valuation identified that participants were very accurate in judging overall attractiveness of choice sets. No condition showed statistical difference from its computational average value (i.e., computational average value of LSET: 6; LSCT: 6; LLCT: 4.5). Moreover, an "unacceptable" item, which was previously classified below one's consideration criterion point, was chosen only for 1.1 trials on average among all the choice trials of a participant. These results together suggest that, although the possible value change of each item value requires independent future studies, the degree of value change, if any, was not large enough to cross over one's consideration criterion point in our study. In reality, there could be numerous factors other than subjective preference that influence our choice process, especially when excluding choice alternatives from our consideration set, for example, time pressure, budget constraint, or perceptual/cognitive limitations. Future research investigating the other drivers that could affect consideration set construction would add important theoretical and practical implications.

Nonetheless, the current findings of this study are important in elaborating and further expanding the existing hypothesis concerning the set size effect, which until now has only focused on the total number of options.

Our results indicate that a positive set size effect, an increase in choice-related positive affective responses, such as choice satisfaction, requires a simultaneous increase in the size of the consideration set and in the degree of contrast among available options. Among the diverse variables related to choice behaviors, choice satisfaction has a particular importance, both to consumers and to suppliers, as a comprehensive measure for evaluating the entire process of choice making. Choice satisfaction remains after decisions have been made, and more importantly, it directly affects subsequent choice behaviors. From the perspective of consumers, choice satisfaction is a critical factor for maintaining their psychological well-being and maximizing their subjective welfare. On the other hand, post-choice consumer satisfaction would also be crucial for suppliers seeking to maximize their benefits by the consumer's repurchasing of products. Therefore, the results of this study not only provide theoretical insight into the understanding of choice behavior and its underlying neural mechanisms but can also help in designing optimal choice assortments that will maximize consumer welfare and suppliers' profits by increasing post-choice satisfaction.

In summary, the current findings suggest that neither an increase in the number of considerable options nor an increase in the degree of preference contrast, by itself, led to positive set size effect. Both are required simultaneously for greater choice satisfaction. Regarding choice difficulty on the other hand, it is demonstrated that either enlarged consideration set or less preference contrast among options would increase choice difficulty. We discovered that consideration set size, the size of the "subjectively reconstructed" choice set, is reflected in the striatum and the dACC. In addition, the striatum and the dACC, respectively, predict choice satisfaction and choice difficulty, which are two major positive and negative affective consequences resulting from increases in consideration set size. These results shed additional light on the processes underlying choice behavior and its consequences, which are largely affected by various psychological contexts, including choice set attributes in this study.

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