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Effects of chewing on cognitive processing speed

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ABSTRACT

In recent years, chewing has been discussed as producing effects of maintaining and sustaining cognitive performance. We have reported that chewing may improve or recover the process of working memory; however, the mechanisms underlying these phenomena are still to be elucidated. We investigated the effect of chewing on aspects of attention and cognitive processing speed, testing the hypothesis that this effect induces higher cognitive performance. Seventeen healthy adults (20–34 years old) were studied during attention task with blood oxygenation level-dependent functional (fMRI) at 3.0 T MRI. The attentional network test (ANT) within a single task fMRI containing two cue conditions (no cue and center cue) and two target conditions (congruent and incongruent) was conducted to examine the efficiency of alerting and executive control. Participants were instructed to press a button with the right or left thumb according to the direction of a centrally presented arrow. Each participant underwent two back-to-back ANT sessions with or without chewing gum, odorless and tasteless to remove any effect other than chewing. Behavioral results showed that mean reaction time was significantly decreased during chewing condition, regardless of speed-accuracy trade-off, although there were no significant changes in behavioral effects (both alerting and conflict effects). On the other hand, fMRI analysis revealed higher activations in the anterior cingulate cortex and left frontal gyrus for the executive network and motor-related regions for both attentional networks during chewing condition. These results suggested that chewing induced an increase in the arousal level and alertness in addition to an effect on motor control and, as a consequence, these effects could lead to improvements in cognitive performance.

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1. Introduction

Recently, behavioral studies were performed to examine the relationship between chewing and cognitive performance including memory, attention and executive function. With regard to memory, it has been reported that gum chewing improves episodic and working memory during chewing, suggesting at least in part that chewing promotes regional cerebral blood flow and glucose delivery (Stephens & Tunney, 2004; Wilkinson, Scholey, & Wesnes, 2002; Zoladz & Raudenbush, 2005). However, the existence of enhanced performance of episodic memory task by context-dependent effects induced by chewing has remained controversial (Baker, Bezance, Zellaby, & Aggleton, 2004; Johnson & Miles, 2007, 2008; Stephens & Tunney, 2004). As for attention, it was reported that sustained attention (Smith, 2009a, 2010; Tucha, Mecklinger, Maier, Hammerl, & Lange, 2004) and language-based attention (Stephens & Tunney, 2004) were improved by chewing. On the other hand, Tucha et al. (2004) claimed not only that memory functions were not improved but also that tonic and phasic alertness were adversely affected by chewing. With respect to executive function, a study claimed that chewing gum does not appear to be of benefit to word association executive function (Stephens & Tunney, 2004), but another study reported a beneficial effect (Onyper, Carr, Farrar, & Floyd, 2011).

To elucidate these inconsistent results and their mechanisms, several functional neuroimaging studies have been conducted. These studies suggested that chewing facilitated the process of working memory and also that it was related to attention

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(Hirano et al., 2008; Wang, Gitelman, & Parrish, 2009). As well, several studies mentioned that chewing affects arousal (Onyper et al., 2011; Sakamoto, Nakata, & Kakigi, 2009; Smith, 2010; Stephens & Tunney, 2004). Sakamoto et al. (2009) studied the effect of chewing on the central nervous system by measuring reaction time (RT) and event-related potentials (ERPs). They suggested that chewing influences the state of arousal via the ascending reticular activating system, and that it accelerates cognitive processing.

Based on these studies, we assumed that chewing also affects aspects of attention and accelerates cognitive processing. Indeed, recent studies, pointing out that reaction times were shortened by chewing in the categoric search task (Allen & Smith, 2012a; Smith, 2010), vigilance task (Allen & Smith, 2012a), language-based attention task (Stephens & Tunney, 2004), and the encoding of new information in the focused attention task (Smith, 2010). Smith (2010) speculated that positive cognitive performance may come from the fact that subjects feel more alert as described, being energetic, quick-witted and attentive, all based on mood improvement. However, some studies reported not only that the performance of sustained attention was not accelerated (Kohler, Pavy, & Van den Heuvel, 2006; Smith, 2010; Tucha et al., 2010) but also that vigilance task was decelerated (Tucha et al., 2010). Tucha et al. (2010) indicated that the psychodynamics of gum chewing might be an important factor, and these conflicts of cognitive performance may originate from the duration of the study (Tucha et al., 2010) and time of the task (Allen & Smith, 2012a, 2012b; Tucha & Simpson, 2011). Indeed, Tänzer, Von Fintel, and Eikermann (2009) reported that chewing benefit in concentration performance showed up after 14 min from the initiation of the test. To elucidate the mechanism of this issue, we considered that a functional magnetic resonance imaging (fMRI) assessment might be helpful. The attentional network test (ANT) provided a way of testing for the efficiency of the alerting, orienting and executive (conflict resolution) functions of attention (Fan, McCandliss, Sommer, Raz, & Posner, 2002), and it was adapted within a single session of event-related fMRI (Fan, McCandliss, Fossella, Flombaum, & Posner, 2005). In the current study, we examined the effects of chewing on alerting and executive attention and their processing speed by comparing the behavioral and fMRI results of ANT.

2. Experimental procedures

2.1. Subjects

Nineteen healthy volunteers (aged 20–34) were enrolled for assessment by random-effect analysis (Seghier, Lazeyras, Pegna, Annoni, & Khateb, 2008) in this study. Two participants were excluded from the analysis due to motion (>0.56 mm, corresponding to 15% of voxel size in-plane) during the fMRI scan. Therefore, data from 17 healthy volunteers (mean age ± SD, 25.2 ± 4.79 years; range, 20–34 years; 8 females) were evaluated in this study. Written informed consent was obtained from all subjects. The subjects briefly practiced ANT outside, and then inside the MRI scanner just before the fMRI scan. Experiments were performed according to the ethical guidelines approved by the Ethics Committee of the National Institute of Radiological Sciences.

2.2. Task paradigm

ANT was adjusted by adding the gum chewing session while keeping the total scan time comparable to the original ANT for the fMRI study of the previous report (Fan et al., 2005) to avoid a reduction in the level of attention. For that reason, we used two cue conditions (no cue and center cue) instead of the three cue conditions (no cue, center cue and special cue) used in their study. As in their study, however, we also used the two target conditions (congruent and incongruent). The cue durations and stimulus intervals were also reduced from 300–11800 ms (mean, 2800 ms) to 300–6800 ms (mean, 1800 ms) and from 3000–15000 ms (mean, 6000 ms) to 3000–8000 ms (mean, 5000 ms), respectively. Fig. 1 shows the gum chewing and the following ANT, which was used for our fMRI study, consisting of a 10-min session during each chewing and control condition. Cues consisted of a crosshair in either bold or the same thickness as the fixation crosshair colored in black against a gray background. Targets consisted of a row of five arrows with arrowheads pointing leftward or rightward either above or below the fixation crosshair. Conflict resolution was introduced by incongruent or congruent stimuli, which showed that the central arrow was either flanked or not. Subjects chewed gum for 10 s at their normal speed ($\sim$1 Hz) according to instructions on the screen every six cue-target trials during chewing condition. The existence of cue before showing target activates the alerting system, and flankers adjacent to a target activate executive control of attention (Fan et al., 2002). Then, during control condition, subjects were instructed not to chew gum. We used moderately hard-type gum (5.6×10^3 Pa·s; Lotte Co., Ltd., Tokyo, Japan) without odor or taste components to remove any effects other than mastication. ANTs were conducted and synchronized with the MRI scanner by using E-Prime software (Psychology Software Tools, Inc., Sharpsburg, PA, USA). Each subject underwent the adapted ANT continuously, with or without chewing gum, in two back-to-back sessions, which were interspersed by a 10-min rest period, during which T1 anatomical images were acquired. The order of conditions was randomized among individuals (eight subjects started with chewing) and a 10-min waiting period, during which T1 anatomical images were acquired, was inserted between the two conditions. Subjects were instructed to press a button with the right or left thumb according to the direction of the centrally presented arrow. Each of the button presses and RTs were also recorded. The following operational definitions of the efficiencies of the attentional networks were used to compare the performance between conditions.

$$\text{Alerting effect} = \text{RT (no cue)} - \text{RT (center cue)}$$

$$\text{Conflict effect} = \text{RT (incongruent)} - \text{RT (congruent)}$$

RT and accuracy for each condition were subjected to three-way repeated analysis of variance (ANOVA) followed by Tukey's post hoc test. Behavioral effects (alerting and conflict effect) and mean RT for each chewing condition were subjected to two-way ANOVA. Estimates of effect size were reported for all ANOVAs (partial eta-squared, h2). Correlation coefficients were calculated between the behavioral effects and RT. All statistical analyses were calculated using SPSS (IBM, Chicago, IL, USA).

2.3. Image acquisition and data analysis

fMRI experiments were performed using gradient-echo echo-planar imaging (TE = 30 ms, TR = 2 s, field of view = 24 cm, slice thickness = 3.8 mm, gap = 0.2 mm, image matrix = 64 $\times$ 64, number of slices = 30, flip angle = 90°). After two fMRI scans, T1-weighted anatomical MR images (sequence = 3D fast SPGR, TE = 1.4 ms, TI = 450 ms, TR = 6.5 ms, field of view 25.6 cm $\times$ 25.6 cm, slice thickness = 1 mm, image matrix = 256 $\times$ 256, number of slices = 196, flip angle = 12°, number of acquisitions = 1) were acquired to help spatial image normalization. Data were acquired by GE Signa Excite 3.0 T MRI equipped with 8-ch phased array coil (GE, Waukesha, WI, USA). fMRI data were analyzed by SPM5 (Wellcome Trust Centre for Neuroimaging, University College London, London, UK). Data from the first five volumes were discarded to avoid transient magnetization. Correction for head

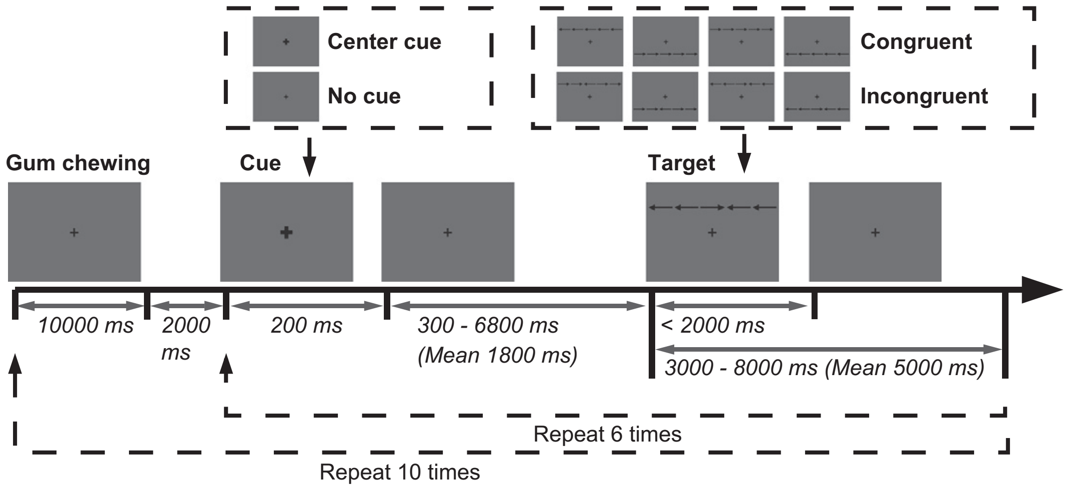

Fig. 1. Schematic depiction of adapted ANT in chewing condition. A fixation cross was constantly shown in the center of the screen. A center cue or no cue was shown for 200 ms randomly. Following a variable duration (300–6800 ms), the center arrow as target and flankers of the left and right two arrows were shown until the subject responded with a button press, but for less than 2000 ms. The target and their flankers disappeared immediately after the subject pressed the button, then the next cue was shown after variable intervals (3000–8000 ms) from the appearance of the target. ANT (Fan et al., 2005) was adapted for this study.

motion was performed. Each of three hundred successive functional images obtained from each subject were normalized to the MNI template (Collins, Neelin, Peters, & Evans, 1994) and spatially smoothed by 8-mm Gaussian kernel. Statistical analysis by general linear model approach (Friston et al., 1995) was performed only for data in parts of ANT to avoid influence of head motion by gum chewing. Global changes in BOLD signals were removed using proportional scaling. After preprocessing, activated areas associated with alerting were isolated by subtracting a no cue condition from a cue condition for first-level individual analysis. Next, activated areas associated with conflict resolution were isolated by subtracting congruent condition from incongruent condition. Finally, random effects group analysis was performed on each chewing condition to estimate activated areas that were consistent for the total group of subjects.

3. Results

3.1. Behavioral analysis

Table 1 shows mean RT and accuracy for each condition. Three-way repeated measures ANOVA of RT showed that the main effects of chewing condition ($F(1,16) = 20.30$, $p < 0.001$, effect size = 0.56), target condition ($F(1,16) = 97.29$, $p < 0.001$, effect size = 0.86), and cue condition ($F(1,16) = 9.03$, $p < 0.01$, effect size = 0.36) were significant. The interactions between chewing condition and target condition ($F(1,16) = 0.78$, effect size = 0.05), chewing condition and cue condition ($F(1,16) = 0.12$, effect size = 0.01), target condition and cue condition ($F(1,16) = 0.11$, effect size = 0.01), and among all three conditions ($F(1,16) = 2.12$, effect size = 0.12), were not significant. Three-way repeated measures ANOVA of accuracy showed that the main effect of target condition ($F(1,16) = 11.39$, $p < 0.005$, effect size = 0.42) was significant. The main effects of chewing condition ($F(1,16) = 0.16$, effect size = 0.01) and cue condition ($F(1,16) = 0.05$, effect size = 0.00) were not significant. The interactions between chewing condition and target condition ($F(1,16) = 1.80$, effect size = 0.10), chewing condition and cue condition ($F(1,16) = 0.05$, effect size = 0.00), target condition and cue condition ($F(1,16) = 0.14$, effect size = 0.00), and among all three conditions ($F(1,16) = 0.11$, effect size = 0.01), were not significant.

Table 2 shows the behavioral effects and mean RT for each chewing condition and the correlation coefficients between behavioral effects and mean RT. Two-way repeated measures ANOVA showed that the main effect of chewing condition was not significant ($F(1,16) = 0.04$, effect size = 0.00), but that the behavioral effect was significant ($F(1,16) = 6.03$, $p < 0.05$, effect size = 0.27). The interaction between chewing condition and behavioral effects was not significant ($F(1,16) = 0.89$, effect size = 0.05). Correlation coefficients between alerting, conflict and mean RT were not significant ($r^2 > 0.20$, $n = 17$, $p \geqslant 0.07$).

3.2. Functional analysis

The attention system is anatomically separated into multiple subsystems from the data processing systems that perform

Table 1
Mean RT ± SD (ms) and accuracies ± SD for each condition.

	Control			After chewing		
	No cue	Center cue	Mean	No cue	Center cue	Mean
Congruent						
RT	545 ± 93	520 ± 91	533 ± 88	510 ± 66	475 ± 60*	493 ± 61
Accuracy	1.00 ± 0.02	0.99 ± 0.03	0.99 ± 0.02	1.00 ± 0.01	1.00 ± 0.01	0.99 ± 0.01
Incongruent						
RT	603 ± 89	569 ± 73	585 ± 75	562 ± 78*	543 ± 62	551 ± 66
Accuracy	0.97 ± 0.06	0.97 ± 0.04	0.97 ± 0.03	0.96 ± 0.06	0.96 ± 0.04	0.96 ± 0.03
Mean						
RT	573 ± 88	545 ± 81	559 ± 80	535 ± 70	511 ± 59	523 ± 62
Accuracy	0.99 ± 0.02	0.98 ± 0.02	0.98 ± 0.01	0.98 ± 0.03	0.98 ± 0.02	0.98 ± 0.02

* Significantly different between chewing conditions ($p < 0.05$).

Table 2
Behavioral effects and correlation coefficients for each chewing condition.

	Control			After chewing		
	Effect ± SD (ms)	Alerting	Conflict	Effect ± SD (ms)	Alerting	Conflict
Alerting	28 ± 48			24 ± 37		
Conflict	52 ± 29	−0.13		58 ± 25	−0.20	
Mean RT	559 ± 80	0.16	−0.45	523 ± 62	0.29	0.22

operations on specific inputs (Posner & Petersen, 1990). In this ANT, alerting is defined as achieving and maintaining an alert state, and executive control is defined as resolving conflict among responses (Fan et al., 2002). For the alerting network, only the left premotor cortex was more activated during chewing condition, while the right postcentral gyrus, anterior lobe of the cerebellum and left superior temporal gyrus were less activated (Fig. 2A and Table 3). On the other hand, for the executive network, while the anterior lobe of the cerebellum was less activated during chewing condition, left middle and superior frontal gyri, right premotor cortex, right precentral gyrus, right anterior and left posterior cingulate gyri, left parietal operculum, left thalamus and left insula were more activated (Fig. 2 and Table 4).

4. Discussion

At first, the main effects of ANT were identified in both cue condition (no cue and center cue) and target condition (congruent and incongruent) in this study (Table 1). The results indicate that our version of ANT was valid with even shorter testing time than that in a past study, which we refer to as modified ANT for fMRI (Fan et al., 2005). Also, the behavioral effects (Table 2) and RT were roughly equivalent (alerting effect was 4% longer and mean RT was 13% shorter) except for conflict effect (58% shorter) compared

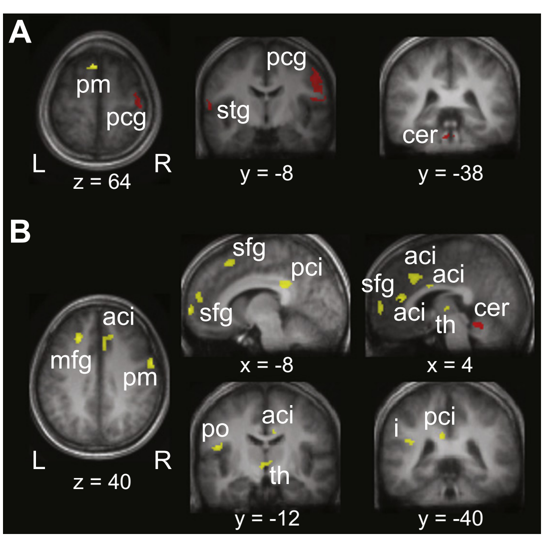

Fig. 2. Significantly different activated regions between chewing and control conditions for the alerting network (A) and the executive network (B). Yellow voxels show more activated regions during chewing condition than control condition. Red voxels show less activated regions during chewing condition than control condition. The statistical threshold was set at $p < 0.01$, uncorrected for multiple comparisons. The extent threshold was set at more than 30 voxels. x, y, and z in cross-sectional view indicate Talairach coordinates (Talairach & Tournoux, 1988). Abbreviations: aci, anterior cingulate gyrus; cer, cerebellum; ci, cingulate gyrus; i, insula; mfg, middle frontal gyrus; pci, posterior cingulate gyrus; pcg, postcentral gyrus; pm, premotor cortex; po, parietal operculum; sfg, superior frontal gyrus; stg, superior temporal gyrus; th, thalamus. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with those in another study of their group (Rueda et al., 2004) conducted for similar test length (∼30 min in total). Our results showed that (i) the attention level would have been kept relatively higher during ANT because the total number of test trials was 45% less, and (ii) subjects could relatively easily wait until the next target was shown while still maintaining attention because the interval was 23% shorter, and especially the longest interval between target and next cue was 47% (7 s) shorter compared with the study of Fan et al. (2005).

The most significant difference in behavioral results between chewing and control conditions was that RT was significantly shorter during chewing condition regardless of any speed-accuracy trade-off. Our results strongly supported previous studies reporting that gum chewing shortened RT to a numerical working memory task (Wilkinson et al., 2002), a sustained alertness (Tucha et al., 2004), an auditory oddball paradigm (Sakamoto et al., 2009), and semantic memory (Smith, 2010). Many reports suggested that chewing activated the frontal cortex (Momose et al., 1997; Onozuka et al., 2003; Sesay, Tanaka, Ueno, Lecaroz, & De Beaufort, 2000; Takada & Miyamoto, 2004; Takahashi, Miyamoto, Terao, & Yokoyama, 2007; Tamura, Kanayama, Yoshida, & Kawasaki, 2003), which may cause improvement in alerting and executive functions assumed to be executed in that region (Fan et al., 2002). In addition, Takada and Miyamoto (2004) suggested that the fronto-parietal network during chewing contributed to higher cognitive processing. More recently, Sakamoto et al. (2009) suggested that shortened RT resulted from shortened cognitive processing time caused by the central nervous system affected by chewing through its complex behavior such as jaw and tongue movement, tactile sensation in the oral cavity, and saliva secretion. Furthermore, Smith (2009b) reported that chewing increased alertness, suggesting improved test performance. Also, several reports have supported the notion that chewing improved sustained attention (Smith, 2009a) and persistent cognitive performance (Hirano et al., 2008; Sakamoto et al., 2009). Thus, the effect of chewing on RT is considered to be related to alertness and attention. Furthermore, we noted that the chewing effect on cognitive performance is not sustained after cessation of chewing, based on the fact that our results were calculated from data during both chewing conditions, with the order of chewing condition randomized and carried out with a 10-min interval in our study. This was consistent with the proposal of recent studies, that the time-limited nature of performance benefits can be attributed to mastication-induced arousal (Onyper et al., 2011), alertness (Allen & Smith, 2012a, 2012b), and mood (Smith, 2009a). These mechanisms are still being debated (Sakamoto et al., 2009; Smith, 2009b), and further investigations will be required to address these issues. Additionally, we consider that chewing might have a stress reduction effect. In general, the environment in the MRI scanner is somewhat stressful mainly due to the acoustic noise during scanning and the confined space. 3 T MRI scanners generate acoustic noise of more than 110 dB while running gradient-echo echo-planar imaging sequence (Price, De Wilde, Papadaki, Curran, & Kitney, 2001). Participants might have experienced feelings of excitement and stress when being positioned in the MRI scanner. Therefore, the positive effects on mood by gum chewing might have reduced stress and affected the performance of the test.

Table 3
Significantly different activated regions between chewing conditions for alerting network: center-cue minus no-cue.

Region	BA	Coordinates			Z score	p-Value	Number of voxels
		x	y	z			
Chewing > Control condition							
L premotor cortex	6	−8	22	64	3.12	0.001	31
Control > Chewing condition							
R postcentral gyrus	3	52	−14	56	3.85	0.000	752
L cerebellum, anterior lobe	–	−4	−38	−26	3.22	0.001	98
L superior temporal gyrus	22	−64	−8	8	2.93	0.002	32

Statistical threshold was set at $p < 0.01$, uncorrected for multiple comparisons.
Extent threshold was set at more than 30 voxels. Voxel size = $2 \times 2 \times 2$ mm^3.
L: left, R: right, BA: Brodmann's area.

Table 4
Significantly different activated regions between chewing and control conditions for executive network: incongruent minus congruent.

Region	BA	Coordinates			Z score	p-Value	Number of voxels
		x	y	z			
Chewing > Control condition							
L middle frontal gyrus	8	−24	26	42	3.49	0.000	191
L superior frontal gyrus	10	−8	68	4	3.28	0.001	184
R premotor cortex	6	58	−2	40	3.23	0.001	108
L superior frontal gyrus	8	−4	24	54	3.07	0.001	139
R anterior cingulate gyrus	32	4	38	16	3.06	0.001	216
L parietal operculum	43	−50	−12	20	3.04	0.001	70
L posterior cingulate gyrus	23	−8	−38	30	3.01	0.001	55
L thalamus	–	−2	−14	2	2.85	0.002	69
L insula	–	−40	−40	24	2.81	0.002	31
R anterior cingulate gyrus	32	4	22	38	2.81	0.002	93
R anterior cingulate gyrus	24	6	4	30	2.71	0.003	39
Control > Chewing condition							
R cerebellum, anterior lobe	–	6	−48	−14	2.79	0.003	69

Statistical threshold was set at $p < 0.01$, uncorrected for multiple comparisons.
Extent threshold was set at more than 30 voxels.

In contrast to the shortened RT, significant changes in behavioral effects (Table 2) were not observed in this study. A limitation to the study might be its rather small sample size, which may have limited the power to sufficiently detect the behavioral effects. However, our results suggest that chewing does not affect alerting and executive function despite the cognitive processing speed being accelerated. Our present fMRI analysis revealed that the premotor cortex was more activated during chewing than control condition for both alerting and executive networks. This indicates that chewing may affect motor control both during alerting and executive function, resulting in increased processing speed. In addition, several regions related to attention such as anterior cingulate gyri and left frontal cortex, expected to be activated on the basis of previous reports (Bush, Luu, & Posner, 2000; Abdullaev, Posner, Nunnally, & Dishion, 2010; Fan, Flombaum, McCandliss, Thomas, & Posner, 2003; Fan et al., 2005; Westlye, Grydeland, Walhovd, & Fjell, 2011), were more activated during chewing condition for the executive network (Fig. 2 and Table 4). These results suggest that chewing increases alerting and attention for the executive network. Also, Bush et al. (2000) suggested that both the dorsal anterior cingulate cortex and areas of the lateral prefrontal cortex operate together during tasks that involve high levels of mental effort. We speculated that the prefrontal cortices synchronously activated the anterior cingulate cortex as well as insula and thalamus during chewing through neural networks among these regions and, consequently, facilitated functional integration for the executive network, in line with a previous study (Beckmann, DeLuca, Devlin, & Smith, 2005).

Although a number of neuroimaging studies have reported that the cerebellum was activated by chewing (Momose et al., 1997; Onozuka et al., 2002, 2003; Otsuka et al., 2009; Sesay et al., 2000), any effects in motor-related regions immediately after chewing were not investigated. For both alerting and executive networks, a less activated region during chewing condition was observed in the anterior lobe of the cerebellum, which is attributable to decreasing activation during hand and eye movement according to the number of sessions by internal model acquisition (Imamizu et al., 2000). In addition, that the premotor cortex was more activated for both alerting and executive networks during chewing condition was supported by the finding that chewing is related to processing the linking of sensory input and motor output (Takada & Miyamoto, 2004; Takahashi et al., 2007). Also, the thalamus, reportedly an activated region for ANT for alerting and executive networks (Fan et al., 2005), was more activated for executive network during chewing condition. Alain et al. (2005) reported that thalamo-cortical activation might reflect higher levels of attention in addition to chewing being regarded as an action-improved alertness (Smith, 2009b; Tucha et al., 2004). Consistent with this, higher activation in the anterior cingulate cortex during chewing condition was shown in our data. Furthermore, Sakamoto et al. (2009) hypothesized that chewing affected the reticular activating system via the thalamus to increase the arousal level by its shortened ERP form. This supported a result that gum chewing improved arousal (Onyper et al., 2011; Sakamoto et al., 2009; Smith, 2010; Stephens & Tunney, 2004). These results suggested that chewing activated motor-related brain regions first, and then these regions increased the arousal level and alertness during ANT. Consequently, these chewing effects contributed to the cognitive processing speed.

In conclusion, chewing accelerated the processing speed of ANT, which measures the efficiency of the alerting and executive networks, but it did not affect the two attentional effects. In addition, brain regions related to motor and attention were more activated during chewing condition. These results suggested that chewing induced an increase in the arousal level and alertness in addition to an effect on motor control and, as a consequence, these effects could lead to improvements in cognitive performance.

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