Local and Global Effects of Prosodic Boundaries: Evidence from Eye Movements

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Lee, Eun-Kyung. (2012). Local and Global Effects of Prosodic Boundaries: Evidence from Eye Movements. *Language Research* 48.2, 223-237

Although several studies have demonstrated that listeners integrate current prosodic boundaries with occurrences of relevant earlier prosodic boundaries in making syntactic attachment decisions (*e.g.*, Carlson et al. 2001; Clifton et al. 2002), these studies have only used offline judgment tasks. The current study instead uses a visual world eye-tracking paradigm to examine whether global prosodic information has immediate impacts on parsing or whether its effects are delayed until after some initial processing of the local boundary. The fixation data showed that prosodic boundaries were interpreted just locally during online processing. There was only weak evidence for the effects of relative boundary strength on the final interpretation of a sentence. The data suggest that prosodic boundaries may be first processed locally and be integrated with relevant earlier boundaries only after a delay.

Keywords: prosodic boundaries, global prosodic structure, attachment ambiguity, eye-tracking, parsing

1. Introduction

A great deal of work has shown that prosodic boundaries can have an influence on syntactic decisions in spoken language comprehension (*e.g.,* Kjelgaard & Speer 1999; Lehiste 1973; Marslen-Wilson, Tyler, Warren, Grenier, & Lee 1992; Price, Ostendorf, Shattuck-Hufnagel, & Fong 1991; Pynte & Prieur 1996; Snedeker & Trueswell 2003; Speer, Kjelgaard, & Dobroth 1996; Warren, Grabe, & Nolan 1995). Prosodic boundaries resolve syntactic attachment ambiguities that result from a constituent possibly being associated with more than one location in the syntactic tree. Consider (1).

(1) *Susie learned (a) that Bill telephoned (b) after John visited.*

In sentence (1), the temporal adjunct "after John visited" can attach either low to the subordinate clause verb "telephoned", which is called low attachment, or high to the main clause verb "learned", which is called high attachment. Previous work has shown that a prosodic boundary between the two potential attachment heads (*i.e.,* a prosodic boundary at (a) in (1)) tends to create a bias towards low attachment while a prosodic boundary before an ambiguous phrase (*i.e.,* a prosodic boundary at (b) in (1)) tends to promote high attachment (*e.g.,* Price et al. 1991; Snedeker & Trueswell 2003).

Over the last decade, divergent hypotheses have been offered to account for how prosodic boundaries create the biases that they do in attachment ambiguity resolution (*e.g.,*Carlson, Clifton, & Frazier 2001; Clifton, Carlson, & Frazier 2002; Marcus & Hindle 1990; Schafer 1997; Watson & Gibson 2005). One hypothesis is that prosodic boundaries provide a signal to syntactic closure (Marcus & Hindle 1991; Watson & Gibson 2005). An example of this type of approach is the Anti-Attachment Hypothesis (Watson & Gibson 2005). The Anti-Attachment Hypothesis proposes that prosodic boundaries provide a cue not to attach incoming lexical items to the most recently processed lexical head. Thus, upcoming elements are less likely to attach to it. In (1), when there is a prosodic boundary at (a), listeners are more likely to interpret the ambiguous temporal adjunct as being associated with the verb "telephoned" because a prosodic boundary after "learned" signals that the preceding lexical head is unlikely to receive further attachment. This theory also accounts for why a prosodic boundary at (b) biases listeners towards attaching the temporal adjunct to the main verb "learned". The presence of a prosodic boundary after a subordinate clause verb "telephoned" closes it for further attachment, leading the temporal adjunct to be more likely to attach to the other attachment head "learned".

Carlson and colleagues (Carlson et al. 2001; Clifton et al. 2002; Carlson, Clifton, & Frazier 2009) have argued thatthe interpretation of syntactic structure is not determined by the position of a local prosodic boundary, but by how a local prosodic boundary interacts with other prosodic boundaries in an utterance. They formalized this as the Informative Boundary Hypothesis, which states that listeners evaluate the informativeness of a prosodic boundary with respect to its strength relative to relevant prosodic boundaries earlier in an utterance. Carlson et al. (2001) manipulated the strength of a prosodic boundary at (b) relative to a prosodic boundary at (a) in sentences like (1). The results demonstrated that a local prosodic boundary at (b) created a main verb modification bias only when it was stronger than a prosodic boundary at (a). The findings show that a prosodic boundary is informative about syntax only when it is stronger than a relevant prosodic boundary at earlier positions in an utterance.

Frazier, Carlson, and Clifton (2006) argue that the Informative Boundary Hypothesis stands in contrast to the Anti-Attachment Hypothesis. However, theories arguing that prosodic boundaries serve as cues to local syntactic structure or serve as points of local processing are not necessarily inconsistent with the global prosodic structure influencing syntactic parsing. Although it is clear that prosodic boundaries are not interpreted in isolation and that the global prosodic structure of an utterance is important in influencing attachment, it is still possible that individual prosodic boundaries provide information about local syntactic structure. The term "local" is used in the sense used by Watson and Gibson (2004): that the presence of a prosodic boundary can influence the dependency relationships between the words next to which the prosodic boundary appears.

Under a constraint-based framework (*e.g.,* MacDonald, Pearlmutter, & Seidenberg 1994; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy 1995), each individual prosodic boundary might serve as a probabilistic cue to syntactic closure, with stronger prosodic boundaries providing stronger cues. Prosodic boundaries at multiple locations in an utterance might provide competing cues to attachment. Competition among these cues may have consequences for how and why global prosodic structure affects syntactic attachment. An unanswered question (pointed out by Carlson et al. 2001) is how rapidly this competition is resolved (*i.e.,* how rapidly information from multiple prosodic boundaries is integrated) to influence syntactic parsing.

To date, the Informative Boundary Hypothesis has been tested only in offline studies. In these studies, participants heard globally ambiguous sentences like (1) manipulated for relative boundary strength, and then they were asked to choose one of the two paraphrases of the sentence that they have heard, which mapped on to high and low attachment interpretations, respectively. (*e.g.,* "Susie learned something after John visited." vs. "Bill telephoned somebody after John visited."). The effect of global prosodic information was assessed by participants' offline judgments, which made it impossible to determine whether global prosodic structure had an immediate impact on interpretation or whether its effects took place after some initial processing of the local prosodic boundary. In (1), the effect of a prosodic boundary at (a) may be integrated into the interpretation of a prosodic boundary at (b) as soon as a prosodic boundary at (b) is encountered with an attachment bias varying depending on information from a prosodic boundary at (a). Alternatively, a prosodic boundary at (b) is initially interpreted as creating a bias towards high attachment, and this interpretation is modulated by global prosodic information (a prosodic boundary at (a) in this case) with a delay.

The current study examines the time course of using global prosodic information in syntactic parsing, using a visual world eye-tracking paradigm. As eye movements are closely time-locked to referring expressions in the speech input, eye movements to objects in a visual display provide highly reliable information about real-time speech processing. Previous studies have found that eye-tracking is also an effective measure of the online processing of prosodic information (Allopenna, Magnuson, & Tanenhaus 1998; Dahan, Tanenhause, & Chambers 2002; Ito & Speer 2008; Snedeker & Trueswell 2003).

The question discussed above was tested using globally ambiguous relative clause sentences like (2) below.

(2) a. (ip, ip): *Click on the candle* **ip** *above the triangle* **ip** *that's in the blue circle.*
b. (ip, IP): *Click on the candle* **ip** *above the triangle* **IP** *that's in the blue circle.*
c. (IP, ip): *Click on the candle* **IP** *above the triangle* **ip** *that's in the blue circle.*
d. (IP, IP): *Click on the candle* **IP** *above the triangle* **IP** *that's in the blue circle.*

The sentence in (2) is ambiguous because the relative clause *that's in the blue circle* can modify either the high noun "candle", or the low noun "triangle". In order to test the Informative Boundary Hypothesis using the types of prosodic boundaries used in previous work (Carlson et al. 2001; Clifton et al. 2002), the strength of prosodic boundaries in two critical positions was varied between the intonational phrase boundary (IP) and the intermediate phrase boundary (ip), which resulted in the 4 conditions illustrated in (2) above. The intermediate phrase boundary is a weaker juncture than the intonational phrase boundary and it is the perceptual equivalent of a "3" in the ToBI coding schemes (Beckman & Elam 1997).

The conditions differed from each other in terms of relative boundary strength. In (2a) and (2d), the strength of the late boundary (*i.e.,* the boundary after "triangle") was equal to that of the early boundary (*i.e.,* the boundary after "candle"). In (2b), the late boundary was stronger than the earlier boundary while in (2c), the late boundary was weaker than the earlier boundary. According to the Informative Boundary Hypothesis, the effect of the late boundary creating a high attachment bias should be stronger in condition (2b) than in (2c). Conditions (2a) and (2d) should lie somewhere in between. The conditions also differed from each other in terms of the absolute strength of the late boundary. Conditions (2b) and (2d) had a stronger intonational phrase boundary while conditions (2a) and (2c) had a relatively weaker intermediate phrase boundary. If the late boundary is interpreted locally, the conditions with an intonational phrase boundary should result in more high attachment than those with an intermediate phrase boundary, regardless of relative boundary strength.

In this experiment, each critical instruction was presented with a visual scene consisting of 4 objects (candles) that were potential referents of the high noun and 4 shapes (triangles) that were potential referents of the low noun, as illustrated in Figure 1. The participants' task was to click on one of the pictures in the visual display according to the instructions. While doing so, their fixations were monitored.

In Figure 1, the correct target for the high attachment interpretation is the candle in a blue circle. For the low attachment interpretation, the correct target is the candle that is paired with the triangle surrounded by a blue circle.

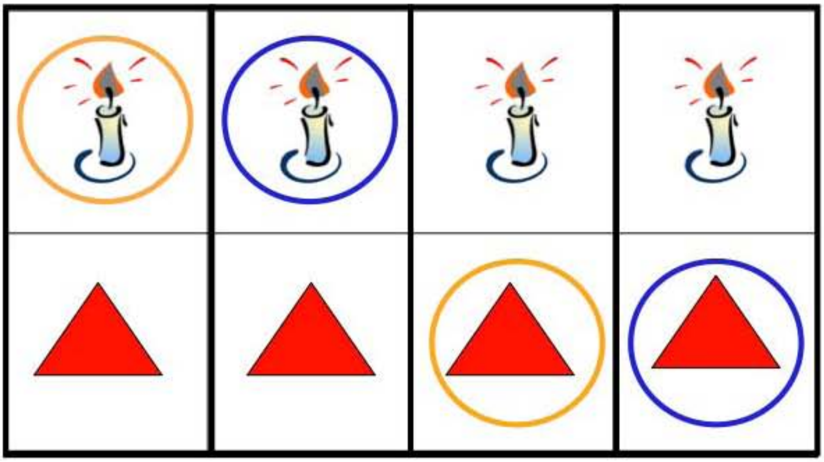

Figure 1. Example visual scene.

The critical measure here is whether the late boundary is interpreted locally or globally at the moment of its presentation. Note that the target is not disambiguated until the information in the relative clause (*e.g.,* in the blue circle) is heard. Thus, the online interpretation of prosodic information at the point of the late boundary is assessed by the combined proportions of fixations to possible referents of the high noun (all 4 candles). If listeners expect an upcoming relative clause to be about the high noun, there should be increased fixations to possible referents of the high noun. On the other hand, if low attachment is expected, there should be fewer fixations to those referents (*i.e.,* more fixations to possible referents of the low noun (triangles)). There are two possible predictions depending on the timing of integrating global prosodic information into the interpretation of the late boundary. If the effects of global prosodic structure takes place after some initial processing of the late boundary creating a bias towards high attachment, there should be more fixations towards possible referents of the high noun when the late boundary is an intonational phrase boundary ((ip, IP) and (IP, IP)) than when it is an intermediate phrase boundary ((ip, ip) and (IP, ip)). If global prosodic structure is integrated immediately, the differences in fixations should be observed in the direction predicted by relative boundary strength: condition (ip, IP) should lead to more fixations towards referents of the high noun than condition (IP, ip) does. Conditions (ip, ip) and (IP, IP) should lie somewhere in between.

2. Method

2.1. Participants

Sixty-four undergraduate students from the University of Illinois at Urbana-Champaign completed the experiment for course credit. Participants were all native English speakers. They had normal or corrected-to-normal vision and no reported hearing impairment.

2.2. Procedure

Participants' eye movements to objects in a visual scene were monitored using an Eyelink 2000 head-mounted eye tracker while they were listening to auditory instructions over speakers. The participants were instructed to click on pictures in the display. Participants' eye fixations were recorded from the onset of the auditory instruction until the selection of the picture. At the beginning of each experimental session, 2 practice trials were provided.

2.3. Materials

Critical items were thirty-two sentences taken from Lee (2012). Each critical sentence consisted of a complex noun phrase followed by a relative clause headed by *that*, as shown in (2) above. The two nouns in the complex noun phrase were linked to each other by locative prepositions. In half of the critical instructions, the locative preposition was *below,* and in the other half, it was *above*. The experimental sentences were produced by a trained female native speaker of American English. The intermediate phrase boundary was produced with a low phrase accent (L-), and the intonational phrase boundary with an L-H% boundary tone.

In order to prevent the results from being confounded with any unintended acoustic differences in the speech stream, the stimuli were cross-spliced. First, the words leading up to the onset of the high noun (*i.e., Click on the*) were cross-spliced so that the initial words in the sentence had no acoustic differences across conditions. The high noun and the words leading up to the onset of the low noun (*i.e., candle above the*) were cross-spliced so that this acoustic region was identical across conditions with the same early boundary ((2a) and (2b), (2c) and (2d)). For the same reason, the rest of the words in the sentence (*i.e., triangle that's in the blue circle*) were cross-spliced across conditions with the identical late boundary ((2a) and (2c), (2b) and (2d)).

Table 1 presents the mean durations of the critical nouns and the post-boundary pauses for each boundary type.

Table 1. Mean durations of HN, LN, and post-boundary pauses (in ms)

	HN	Pause after HN	LN	Pause after LN
ip	461 (11.7)	34 (2.4)	472 (10.6)	33 (1.4)
IP	624 (10.7)	215 (2.2)	646 (14.1)	215 (2.6)

Note. Standard errors are presented in parentheses.

The mean durations of the pre-boundary words were longer when they were followed by intonational phrase boundaries than by intermediate phrase boundaries and the differences were reliable (HN: $t(31) = 25.7$, $p < .0001$, LN: $t(31) = 24.9$, $p < .0001$). The post-boundary pauses were also longer after intonational phrase boundaries than after intermediate phrase boundaries (pause after HN: $t(31) = 56.5$, $p < .0001$, LN: $t(31) = 56.4$, $p < .0001$). Table 2 presents the mean values of the low f0 target (L-) and of the high f0 target (H%) at the end of the critical nouns.

Table 2. Mean F0 values at L- and H% (in Hertz)

	HN		LN	
	L-	H%	L-	H%
ip	184 (2.8)		163 (2.7)	
IP	167 (2.7)	207 (2.0)	156 (2.3)	202 (1.8)

Note. Standard errors are presented in parentheses.

The comparison within each critical noun showed that the mean f0 minimum of intonational phrase boundaries was reliably lower than that of intermediate phrase boundaries (HN: $t(31) = 4.6$, $p < .0001$, LN: $t(31) = 2.3$, $p < .05$).

Eight lists were constructed out of 256 sentences (32 sentences × 4 prosodic boundary conditions × 2 types of locative prepositions). Critical items were rotated through 4 boundary conditions across lists.

Each item occurred only once in one of the 4 prosodic conditions within the list, but occurred in all conditions across lists. The type of locative prepositions was also counterbalanced across lists. Each item occurred with *below* in half of the lists and with *above* in the other half. Each list contained 32 critical items (8items per condition) and 96 distracter items. As in the test sentences, the distracter sentences included locative prepositions, requiring participants to figure out the spatial relationship between objects and shapes in the visual display to find target pictures. Sixty out of 96 distracters were simpler in structure than the test sentences in that they contained only one word indicating the spatial relationship: Each of the prepositions *above, below* and *in* occurred in sixteen distracters each (*e.g., Click on the alarm clock [that's] above the gray triangle, Click on the car [that's] below the orange cube, Click on the triangle [that's] in the purple circle.)*. Twelve distracters included *next to* (*e.g., Click on the cage [that's] next to the blue arrow.*). In another twelve distracters, the spatial relationship was expressed in two dimensions (*e.g., Click on the coffee maker above the pink heart and next to the blue square.*). The other twenty-four distracters were potentially ambiguous like the test items, but the ambiguity was resolved by the visual display that conveyed only one reading (*e.g., Click on the plate in the green circle [that's] next to the triangle. Click on the harp [that's] next to the arrow in the gray circle.*). The experimental and distracter sentences were presented in arandomized order.

3. Results

3.1. Selection Data

The selection data reflect participants' final, offline interpretation of relative clause attachment ambiguities. Table 3 presents the proportion of high attachment interpretation responses by condition.

Table 3. Proportion of high attachment interpretation responses

(ip, ip)	(ip, IP)	(IP, ip)	(IP, IP)
.13	.16	.11	.14

As shown in Table 3, participants clicked on the high attachment target only 13% of the time on average, showing an overall preference for low attachment. There were more high attachment interpretation choices when the late boundary was an intonational phrase boundary ((ip, IP) and (IP, IP)) than when it was an intermediate phrase boundary ((ip, ip) and (IP, ip)). Consistent with Lee (2012)'s findings, a 2-way ANOVA with early boundary (ip vs. IP) and late boundary (ip vs. IP) as within-subjects factors revealed that there was a main effect of late boundary ($F1(1,63) = 6.3$, $p < .05$, $F2(1,31) = 5.8$, $p < .05$). The effect of the early boundary was not reliable ($F1(1,63) = 2.1$, $p > .1$, $F2(1,31) = 2.3$, $p > .1$). There was no reliable interaction (F's < 1). Although the statistical results suggest that listeners interpreted the late boundary just locally, note that the mean proportions are in the direction predicted by the Informative Boundary Hypothesis. I discuss this later in the Discussion.

3.2. Fixation Data

The proportion of fixations to each picture was calculated out of the fixations to all eight pictures after resynchronizing the data at the onset of the relative clause (*i.e.,* the offset of the late boundary). Samples were taken every 25 ms.

Figure 2 presents a time course of the proportions of fixations to possible referents of the high noun (*i.e.,* Targets) at the onset of the relative clause.

The data before the alignment point (*i.e.,* -300~0 ms) shows that participants' fixations stayed longer on the referents of the pre-boundary word (triangles) (*i.e.,* less looks towards candles) when the low noun (*triangle*) was followed by intonational phrase boundaries than by intermediate phrase boundaries, and this difference was reliable ($F1(1,63) = 11.1$, $p < .01$, $F2(1,31) = 11.4$, $p < .01$).

This pattern of fixations was reversed in the time window 0~200 ms after the onset of the relative clause, revealing more fixations towards the Targets (candles) when the late boundary was an intonational phrase boundary than when it was an intermediate phrase boundary. Given that it takes roughly 200 ms to program an eye movement (Allopenna et al. 1998), this pattern of the results indicates that the effect of the late boundary came about even before eye movements

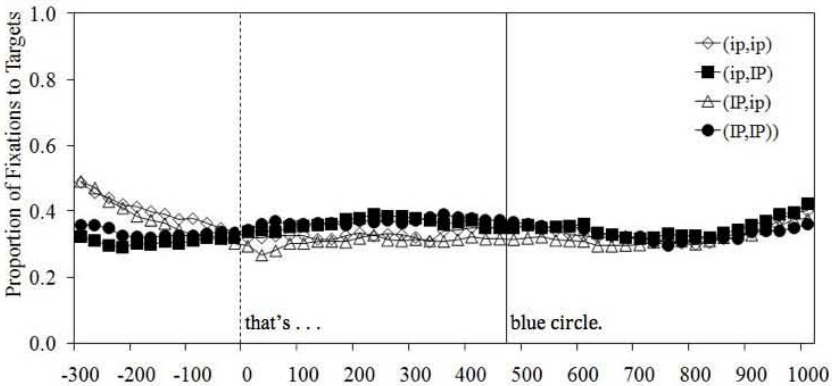

Figure 2. Fixation proportions to the Targets with the utterances synchronized at the onset of the relative clause (*i.e.*, 0 ms corresponds to the onset of *that's*). The shaded symbols indicate the conditions in which the late boundary was an intonational phrase boundary ((ip, IP) and (IP, IP)) while un-shaded symbols indicate the conditions in which the late boundary was an intermediate phrase boundary ((ip, ip) and (IP, ip)). The solid vertical line indicates the average onset of the color adjective in the relative clause (*blue*) across conditions.

could not yet have been initiated on the basis of auditory information about the relative clause. A 2-way ANOVA showed that there was a main effect of late boundary ($F1(1,63) = 5.2$, $p < .05$, $F2(1,31) = 5.2$, $p < .05$). There was nomain effect of early boundary and no interaction. Because prosodic boundaries can be signaled by changes in F0 and duration on the pre-boundary word, this early effect seems to be attributable to the fact that listeners had prosodic boundary information earlier than the point at which fixations were aligned.

The same pattern of fixations was sustained over the 200~500 ms time window where eye movements responding to the auditory input of the relative clause had been initiated. There was a reliable difference between the conditions with late boundaries and without ($F1(1,63) = 5.9$, $p < .05$, $F2(1,31) = 9.4$, $p < .01$). There was no main effect of early boundary, nor was there a reliable interaction (F's < 1).

Taken together, the results suggest that late boundaries were initially interpreted just locally.

4. Discussion

Listeners integrate current boundary information with previous occurrences of prosodic boundaries in making inferences about syntactic structure (*e.g.,* Carlson et al. 2001). The current study tested whether global prosodic information has immediate impacts on the interpretation of ambiguous structures or whether its effects are delayed until after some initial processing of the local boundary.

In both the fixation and the selection data, there was a reliable effect of just the late boundary, which is consistent with the prediction of the Anti-Attachment Hypothesis. There was no reliable effect of the early boundary nor was there a reliable interaction between the early and late boundaries. The absence of an effect of the early boundary and of an interaction appears to be inconsistent with the prediction of the Informative Boundary Hypothesis. However, the numeric pattern of the means in the offline selection data was in the direction predicted by the Informative Boundary Hypothesis. The (ip, IP) condition elicited a higher proportion of high attachment responses (.16) than the (IP, ip) condition (.11) with the conditions with two boundaries of equal size located in between (.13 and .14).

Given that previous studies have found a reliable effect of global prosodic structure on the participants' offline interpretation of an ambiguous phrase (*e.g.,* Carlson et al. 2001; Carlson et al. 2009; Clifton et al. 2002), only weak evidence for the Informative Boundary Hypothesis in the current data may, of course, be due to a lack of power. The offline measure employed here may not have been sensitive enough to detect existing effects of global prosodic structure. In the offline tasks used in previous work, listeners were required to make overt judgments about interpretation, which may have led them to be explicitly aware of the ambiguity or the prosodic differences among conditions.

The lack of statistical support for the Informative Boundary Hypothesis might also be due to a floor effect given that there were strong low attachment preferences in the current data. First, an overall preference for low attachment could be due to the relative frequency of the two structures in English with low attachment structures more frequent than high attachment structures (Cuetos & Mitchell 1988; Gilboy, Sopena, Clifton, & Frazier 1995). The second reason seems to be pragmatic: in the high attachment reading, the referring expression *the* *candle above the triangle* may have been less felicitous than in the low attachment reading because the definite determiner *the* was used before the word *triangle* even though there was not a unique triangle in the display. The use of the definite determiner in combination with the display might have led listeners to be more likely to expect post-nominal modification of the low noun *triangle*. Thus, it is possible that listeners' sensitivity to global prosodic structure interacted with default syntactic preferences. In the current data, given that low attachment was structurally preferred, the effect of early boundaries may have been relatively weak in interpreting the late boundary because they provided redundant information.

The current study has implications for understanding how multiple prosodic cues are processed in parsing. The results demonstrated that the late boundary had immediate impacts on eye gaze, leading to faster fixations to the referents of the high noun (*i.e.,* candles) when it was an intonational phrase boundary than when it was an intermediate phrase boundary. The fixation data suggest that prosodic boundaries are interpreted as cues to local syntactic structure initially. The numeric pattern of the offline data provides weak evidence that there may be a role the global prosodic structure of an utterance plays in syntactic ambiguity resolution, and its effects may be limited to post-interpretive processes.

As discussed above, only weak evidence for the effects of relative boundary strength may be due to an interaction with default attachment preferences. For a stronger test of the time course of global prosodic information, further research is required using structures with more balanced ambiguities.

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Received : June 25, 2012
Revised version received: July 17, 2012
Accepted: July 27, 2012