Psychonomic Bulletin & Review
2010, 17 (3), 421-426
doi:10.3758/PBR.17.3.421

Target-uncertainty effects in attentional capture: Color-singleton set or multiple attentional control settings?

Charles L. Folk and Brian A. Anderson
Villanova University, Villanova, Pennsylvania

Previous spatial cuing studies have shown that the capture of spatial attention is contingent on top-down attentional control settings whose specificity varies as a function of the certainty of the defining features of the target. For example, when the target is a singleton defined by one specific color, observers adopt a control setting for that color. When the target can be one of two possible colors, however, observers appear to adopt a control setting for color singletons in general (see, e.g., Folk & Remington, 2008). The present study tested whether such results instead reflect the simultaneous maintenance of control settings for multiple colors (Adamo, Pun, Pratt, & Ferber, 2008). Observers searched for targets that were unpredictably red or green, preceded by spatial cues that were red, green, or blue. All three cue types produced evidence of capture, consistent with a general set for color singletons rather than the maintenance of multiple control settings.

It is well established that the allocation of visual attention to objects or locations in space can proceed voluntarily—in accordance with explicit goals of the observer—or involuntarily—in response to salient stimulus events (Jonides, 1981; Posner, 1980; Yantis & Jonides, 1984). There is also evidence that the latter form of attention allocation, referred to as *attentional capture*, can be modulated by the establishment of a top-down "set" related to the explicit, or even implicit, demands of an experimental task. For example, in a series of studies using a modified spatial cuing task, Folk and colleagues (Folk & Remington, 1998; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994) found that the degree to which an irrelevant (i.e., uninformative) spatial cue produces evidence of attentional capture is dependent on whether the cue carries the defining property of the target. Thus, if a target is defined as the red character in the target display, red cues produce evidence of capture (i.e., a cue validity effect) but green cues do not, whereas when the target is defined as the green character, green cues produce capture and red cues do not (Folk & Remington, 1998).

These types of results suggest that when the defining property (e.g., the specific color) of the target is known with certainty, the attention allocation system establishes a "control setting" for that property, so that any stimulus matching the control setting will elicit a shift of attention, even if that shift is to a stimulus known to be irrelevant, such as an uninformative spatial precue. This theoretical proposal has been referred to as *contingent attentional capture* (CAC; but see Theeuwes, 1992, for an alternate theoretical view). An important goal in the research on CAC is to explore the nature of top-down control settings. For example, one question concerns the *specificity* of attentional control settings. Originally, the evidence suggested that control settings are limited to fairly broad stimulus categories, such as static versus dynamic discontinuities (Folk et al., 1994). Subsequent research, however, established that control settings can consist of specific values along particular feature dimensions, such as a specific hue along the color dimension, as described above (Folk & Remington, 1998).

Another, related question concerns the *flexibility* of attentional control settings—that is, to what extent can the attentional control system adopt variable control settings in response to the demands of a task? A recent study by Folk and Remington (2008) suggested that the specificity of attentional control settings can indeed vary adaptively with task demands. One condition of the study replicated the design of Folk and Remington (1998), in which observers searched for a target of a particular color, preceded by an uninformative cue of the same or different color (mixed within blocks). As in Folk and Remington (1998), only same-color cues produced evidence of attentional capture, suggesting that observers had adopted an attentional control setting for the known target color. In another condition, however, on any given trial the target was either (unpredictably) red or green. In this condition, attentional capture was evident regardless of whether the cue color matched the target color on that trial (see also Folk, Leber, & Egeth, 2008). The authors concluded that when the target color is unpredictable, observers adopt an attentional

C. L. Folk, charles.folk@villanova.edu

control setting for color singletons in general rather than for a specific color. It thus appears that the specificity of attentional control settings can vary flexibly as a function of task demands.

A recent study by Adamo, Pun, Pratt, and Ferber (2008) has suggested that there may be an alternative interpretation of the latter result, however. In Adamo et al., participants were required to respond to targets of one color at one location in space, and to targets of a different color at a different location in space (e.g., respond to red targets on the left and to green targets on the right). Uninformative color precues produced evidence of attentional capture only when the cue color matched the assigned target color for the cued location. The authors concluded that separate attentional control settings can be maintained simultaneously at distinct spatial locations. Given this demonstrated ability to maintain multiple control settings simultaneously, it is possible that the capture observed in Folk and Remington (2008) when target color was uncertain may not have reflected a change in the specificity of the top-down control settings (i.e., the adoption of a set for color singletons in general) but may instead have been due to the simultaneous maintenance of attentional control settings for the two possible target colors. The capture of attention by a red cue paired with a green target, for example, might reflect the fact that observers are simultaneously set for both red and green singleton targets, rather than generally set for any color singleton. This is an important theoretical issue, because the notion that the specificity of attentional control settings can vary as a function of task demands has played an important role in the interpretation of a number of previous studies of attentional capture (e.g., Bacon & Egeth, 1994; Burnham, 2007; Folk, Leber, & Egeth, 2002, 2008; Lamy, Leber, & Egeth, 2004). In the debate over the degree to which attentional capture can be modulated by a top-down set, for example, it has been argued that evidence for purely stimulus-driven attentional capture (e.g., Theeuwes, 1992) can be reinterpreted in terms of the adoption of a top-down set for singletons in general (Bacon & Egeth, 1994). Evidence that such apparent flexibility in the specificity of attentional control may actually reflect the ability to maintain multiple specific control settings would therefore have important implications for models of attentional capture and, more generally, for the functional architecture of attentional control.

In order to distinguish between the color-singleton-set account and the multiple-control-settings account, the present study replicated the uncertain-target condition of Folk and Remington (2008) but included a third possible cue color (blue). Participants were presented with a target that was unpredictably red or green, preceded by an uninformative cue that was red, green, or blue. If the uncertainty of the target color results in a top-down set for color singletons in general, then all three cue colors should capture attention, because all three cues are color singletons and are therefore consistent with the control setting. If participants adopted and maintained simultaneous attentional control settings for red and green (i.e., only the target colors), however, then red and green cues should have captured attention, but blue cues should not have because they do not match either of the control settings.

EXPERIMENT 1

Method

Participants. Thirteen undergraduate students were recruited from the Villanova University human participant pool. All were screened for normal or corrected-to-normal visual acuity and color vision. Participants were compensated for their time with credit toward fulfillment of a class research requirement.

Apparatus. Stimulus displays were presented on a Princeton Graphics Ultrasync monitor that was driven by a Zenith 386 microcomputer equipped with a Sigma Design, Color 400 graphics board. The monitor was placed at eye level inside a black wooden viewing box 50 cm from lensless goggles that were attached to a porthole in the front of the box. All but the screen of the monitor was occluded by a black baffle inside the box.

Stimuli. Each trial involved the presentation of a fixation display, a cue display, and a target display (see Figure 1). The fixation display consisted of a fixation square (0.34º × 0.34º visual angle) surrounded by four peripheral boxes (1.15º × 1.15º) placed 4.1º above, below, to the left of, and to the right of fixation. All boxes were light gray (IBM color designation #8) against the black background of the CRT screen.

The cue display consisted of the fixation display with the addition of four sets of four small circles (0.23º in diameter) in diamond configurations, each set surrounding one of the four peripheral boxes. Three of the sets of circles were white (IBM color #15), and one set of circles was red (IBM color #12), green (IBM color #10), or blue (IBM color #9).

The target display consisted of the fixation display with the addition of an "X" or "=" in each of the peripheral boxes. These characters subtended approximately 0.57º in height and width. Three

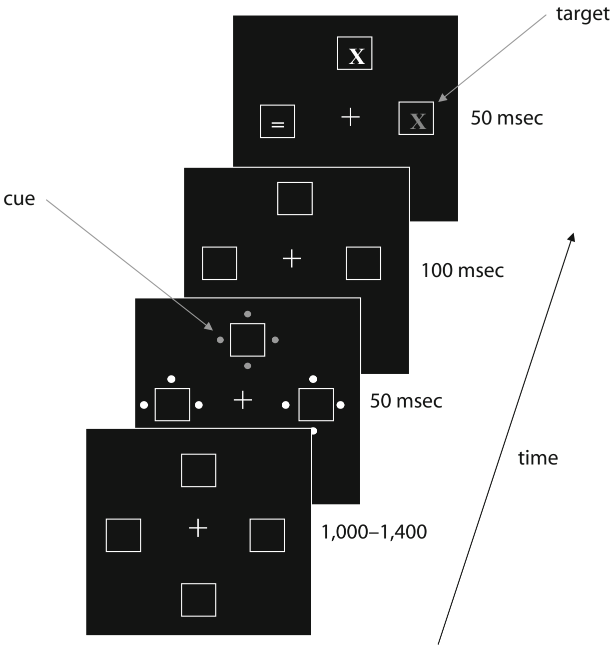

Figure 1. Representation of stimuli and trial events.

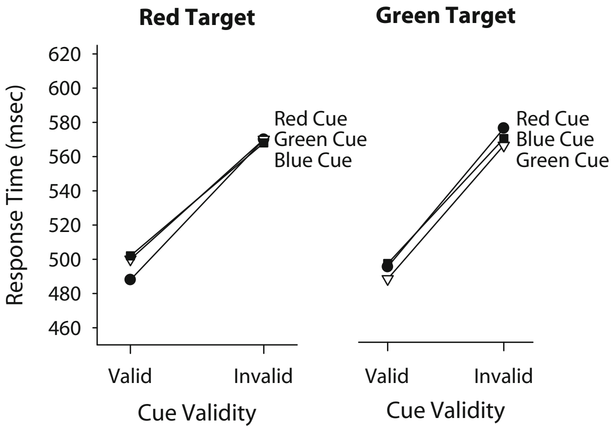

Figure 2. Mean response time as a function of cue color and cue validity for red and green targets in Experiment 1.

of the characters were white, and one (the target) was either red or green.

Design and Procedure. The experiment consisted of eight blocks of 48 trials. Within each block, cue color (red, green, blue) and target color (red, green) were fully crossed to create six conditions: red cue–red target, green cue–red target, blue cue–red target, red cue–green target, green cue–green target, and blue cue–green target. Within each of these conditions, target and cue locations were chosen randomly for each trial with the constraint that cue location was uncorrelated with target location across trials. Specifically, for each cue color–target color combination, the target and cue appeared at the same location on 25% of the trials within a block and at different locations on the remaining 75% of the trials. The identity of the characters (X or =) that appeared in the three nontarget locations was chosen randomly on each trial.

Participants were tested in a dimly lit laboratory room. Written and oral descriptions of the stimuli and procedures were provided in order to familiarize participants with the task. Participants were instructed to respond "as quickly as you can," but they were also encouraged to "make as few errors as possible." Maintaining fixation on the central square was stressed highly, and participants were told that shifting their eyes would impair performance overall. Participants were also fully informed of the relationship between distractor location and target location, and they were told that they should "ignore the cue."

At the beginning of each individual trial sequence, the central fixation square and four surrounding boxes were presented for 500 msec. The fixation square then blinked off for 100 msec and then back on for a randomly varying foreperiod of 1,000, 1,100, 1,200, 1,300, or 1,400 msec. The cue display then appeared for 50 msec, followed by the presentation of the fixation display for 100 msec. The target display then appeared for 50 msec, followed once again by the fixation display. The next trial sequence was initiated 1,000 msec after a response was made. Phenomenally, the four display boxes and the fixation square appeared to remain on the CRT screen for the duration of each trial, as well as during the intertrial interval. The stimulus onset asynchrony between cue and target was 150 msec, making contamination of response times (RTs) by eye movements unlikely.

Participants made a forced-choice target identification by pressing the "." and "0" keys on the numeric keypad of the keyboard for the "X" and "=" targets, respectively (the keys were labeled appropriately). The "X" response was assigned to the right index finger, and the "=" response was assigned to the left index finger. RTs were measured from the onset of the target display. If a response was not initiated within 1,500 msec, an error was scored and the next trial sequence was initiated. Incorrect responses elicited a 500-msec, 1000-Hz computer tone, and they were followed by a "buffer" trial with parameters drawn randomly from the set for that block. RTs for error and buffer trials were not included in the data analysis.

Results

Mean RTs for valid and invalid trials as a function of target color and cue color are shown in Figure 2, and error rates in Table 1. These data were subjected to a $3 \times 2 \times 2$ ANOVA, with cue color (red, green, blue), target color (red, green), and cue validity (valid, invalid) as within-subjects variables. Only the main effect of cue validity was significant [$F(1,12) = 99.15$, $p < .0001$]. A similar analysis of error rates also yielded a main effect of cue validity only [$F(1,12) = 5.80$, $p < .05$], with valid cues producing slightly higher error rates than did invalid cues. Given the large cue validity effects on RT, it is unlikely that the small reverse effects in error rates implicate a speed–accuracy trade-off.

Discussion

The results of this experiment are clear. As in Folk and Remington (2008), when participants searched for a target that could be either red or green, both red and green cues produced evidence of attentional capture (i.e., a significant cuing effect), even when the color of the cue on a specific trial did not match the color of the target on that trial. More importantly, blue cues also produced evidence of attentional capture, which is inconsistent with the hypothesis that participants were simultaneously "set" for red and green target colors. Instead, the results suggest that participants adopted an attentional set for color singletons in general.

Table 1
Error Rates (Proportion) by Target Color, Cue Color, and Cue Validity

Cue	Red Target			Green Target		
Validity	Red Cue	Green Cue	Blue Cue	Red Cue	Green Cue	Blue Cue
Experiment 1						
Valid	.03	.04	.05	.02	.06	.04
Invalid	.04	.03	.03	.02	.02	.03
Experiment 2						
Valid	.05	.03	.05	.06	.05	.04
Invalid	.03	.03	.03	.02	.04	.02

EXPERIMENT 2

Although the results of Experiment 1 are consistent with the adoption of a set for color singletons, one might argue that participants actually *were* simultaneously set for red and green targets, but that the salience of the blue cues was such that they were able to override the top-down set (Theeuwes, 1992). Given that the targets in Experiment 1 were never blue, for example, it is possible that blue cues were particularly salient because they were the only cues to carry a nontarget color. That is, perhaps blue cues stood out precisely because they were not part of the set of colors that defined the target singletons. To address this possibility, participants in Experiment 2 were presented with the same three cue colors, but the target color on each trial was fixed at either red (for half of the participants) or green (for the other half). Since the target could appear in only one color, therefore, participants were 100% certain with respect to the particular target color. As discussed above, previous studies have shown that when target color is certain, participants are able to establish a top-down set for the target color, so that only cues that match the target color produce evidence of attentional capture (e.g., Folk & Remington, 1998). If the blue cues in Experiment 1 were able to override a simultaneous set for red and green by virtue of the fact that targets were never blue, then they should show the same effect in Experiment 2. If, however, the capture of attention by blue cues in Experiment 1 reflects the adoption of a set for color singletons, then they should no longer produce capture in the presence of a top-down set for a nonblue target color.

Method

Participants. Twenty undergraduate students were recruited from the Villanova University human participant pool. All were screened for normal or corrected-to-normal visual acuity and color vision. Participants were compensated for their time with credit toward fulfillment of a class research requirement. None of the participants had taken part in Experiment 1.

Apparatus and Stimuli. The apparatus and stimuli were identical to those used in Experiment 1.

Design and Procedure. The design and procedure were identical to those used in Experiment 1 with the exception that any given participant was presented with only targets of a single color. Specifically, half the participants searched for a red target, and half searched for a green target. Participants were thus 100% certain with respect to the target color, which was assumed to encourage the adoption of an attentional set for the specific target color. The experiment consisted of four blocks of 96 trials.

Results

Mean RTs for valid and invalid trials as a function of target color and cue color are shown in Figure 3, and error rates are shown in Table 1. These data were subjected to a 3 × 2 × 2 mixed ANOVA, with target color as the single between-subjects variable and with cue color (red, green, blue) and cue validity (valid, invalid) as within-subjects variables. The analysis yielded a main effect of cue color [$F(2,36) = 7.26$, $p < .01$] and cue validity [$F(1,18) = 35.41$, $p < .001$]. Cue color entered into interactions with target color [$F(2,36) = 7.39$, $p < .01$] and cue validity [$F(2,36) = 16.47$, $p < .001$]. These interactions were qualified by a three-way interaction between target color, cue color, and cue validity, however [$F(2,36) = 20.62$, $p < .001$]. Simple interaction comparisons of the effects of cue color and cue validity yielded significant interactions for both red target color [$F(1,18) = 23.13$, $p < .001$] and green target color [$F(2,18) = 15.29$, $p < .001$]. Simple effects analyses of the influence of cue validity at each level of cue color yielded significant cuing effects when the cue color matched the target color in both target color conditions [red cues paired with red targets, $F(1,9) = 75.7$, $p < .001$; green cues paired with green targets, $F(1,9) = 36.82$, $p < .001$]. Red cues produced no cue validity effect when paired with green targets, but green cues did produce a small but reliable validity effect when paired with red targets [$F(1,9) = 5.10$, $p = .049$]. Note, however, that the magnitude of this effect was much smaller than the effect when the same green cues were paired with green targets. Most importantly for the present purposes, the cue validity effect for blue cues did not approach significance in either target color condition [red target, $F(1,9) = 0.001$, $p = .97$; green target, $F(1,9) = 1.73$, $p = .22$].

A 3 (cue color) × 2 (target color) × 2 (cue validity) mixed ANOVA conducted on error rates revealed a main effect of cue validity only [$F(1,18) = 9.62$, $p < .05$]. As in Experiment 1, error rates were higher for valid cues than for invalid cues. These effects were again small, however, and did not interact with any other variables; thus, they do not represent a challenge to the interpretation of the RT effects.

Discussion

As is evident in a comparison between Figures 2 and 3, when participants were certain with respect to the target color, the very same set of cues used in Experiment 1 produced dramatically different results. Specifically, whereas all three cue colors produced evidence of attentional cap-

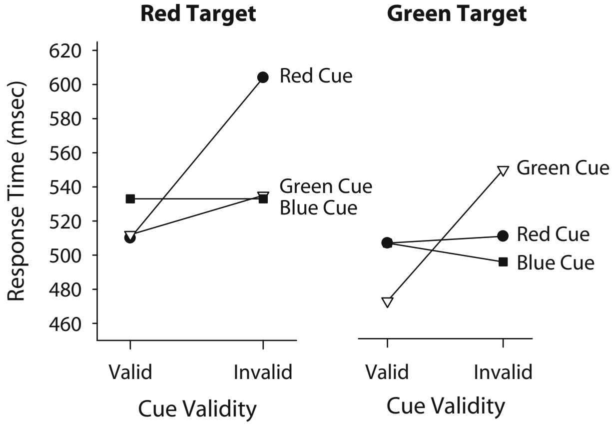

Figure 3. Mean response time as a function of cue color and cue validity for red and green targets in Experiment 2.

ture (i.e., cue validity effects) in Experiment 1, only cues that matched the target color produced reliable evidence of attentional capture in Experiment 2. Most importantly, blue cues produced no evidence of capture in Experiment 2. This suggests that blue cues were unable to override a top-down set for a specific color, which, in turn, suggests that the capture associated with blue cues in Experiment 1 does indeed reflect the adoption of a top-down set for color singletons and not a simultaneous set for the two target colors.

GENERAL DISCUSSION

Previous research with the modified spatial cuing paradigm has suggested that attentional control settings can vary flexibly in terms of specificity as a function of the degree of certainty regarding the specific defining properties of the target. When the color of the target is known with certainty, for example, observers adopt control settings for that color. When the target is unpredictably one of two colors, observers appear to adopt a more general control setting for color singletons in general (Folk & Remington, 2008). This notion that attentional control settings can vary with respect to specificity has played an important role in theoretical treatments of research on attentional capture (Burnham, 2007). Recent evidence that observers are able to maintain multiple attentional control settings simultaneously (Adamo et al., 2008), however, suggests that what appears to be a set for color singletons may instead reflect such multiple control settings. The present studies were conducted to distinguish between these two possibilities in the context of search for color singleton targets in the modified spatial cuing paradigm.

In Experiment 1, target color was varied unpredictably between red and green, whereas cue color varied among red, green, and blue. It was reasoned that if observers adopt simultaneous control settings for red and green, then red and green cues should capture attention but blue cues should not. If, however, observers adopt a set for color singletons, then all three cue colors should produce attentional capture. Consistent with the latter prediction, all three cue colors produced significant cue validity effects of statistically equivalent magnitude. Experiment 2 ruled out the possibility that blue cues were able to override a top-down set for specific colors by showing that when target color was certain (allowing observers to adopt a control setting for the specific target color), blue cues did not produce evidence of attentional capture; only cues that matched the target color produced reliable cue validity effects. The results of the present study thus provide strong evidence that observers can indeed adopt attentional control settings that vary in specificity, so that under conditions of target uncertainty the attention allocation system can be configured to respond to color singletons in general.

It is important to note that the present results in no way call into question the ability to maintain multiple specific control settings simultaneously (Adamo et al., 2008). The present results simply show that under conditions of target uncertainty, the system can, in fact, adopt a more general set for feature singletons. That is, the present study provides strong evidence that the specificity of attentional control settings can indeed vary as a function of task demands. Of course, one might question why, if simultaneous multiple control settings are possible, they were adopted by observers in the Adamo et al. study but not in the present experiments. One important difference between the present study and that of Adamo et al. is the fact that in the latter study behavioral responses were tied to specific combinations of target color and location (i.e., participants were instructed to respond only when a particular combination of color and location occurred), whereas in Experiment 1 of the present study, behavioral responses could be based on the "singleton-ness" of the color target rather than on the specific color of the target. In other words, the design of Adamo et al. did not allow the use of a color-singleton detection strategy. One might also speculate that the adoption and maintenance of simultaneous control settings requires more cognitive effort than does the adoption of a set for color singletons in general. Although adoption of multiple control settings may have prevented capture by blue cues in the present study, overall efficiency may have been maximized by adopting the more general set for color singletons once the cognitive effort involved in maintaining control settings is taken into account.

AUTHOR NOTE

B.A.A. is now at Johns Hopkins University. Correspondence concerning this article should be addressed to C. L. Folk, Department of Psychology, Villanova University, Villanova, PA 19085 (e-mail: charles.folk@villanova.edu).

REFERENCES

Adamo, M., Pun, C., Pratt, J., & Ferber, S. (2008). Your divided attention, please! The maintenance of multiple attentional control sets over distinct regions in space. *Cognition*, **107**, 295-303.

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception & Psychophysics*, **55**, 485-496.

Burnham, B. R. (2007). Displaywide visual features associated with a search display's appearance can mediate attentional capture. *Psychonomic Bulletin & Review*, **14**, 392-422.

Folk, C. L., Leber, A. B., & Egeth, H. E. (2002). Made you blink! Contingent attentional capture produces a spatial blink. *Perception & Psychophysics*, **64**, 741-753.

Folk, C. L., Leber, A. B., & Egeth, H. E. (2008). Top-down control settings and the attentional blink: Evidence for nonspatial contingent capture. *Visual Cognition*, **16**, 616-642.

Folk, C. L., & Remington, R. [W.] (1998). Selectivity in distraction by irrelevant featural singletons: Evidence for two forms of attentional capture. *Journal of Experimental Psychology: Human Perception & Performance*, **24**, 847-858.

Folk, C. L., & Remington, R. W. (2008). Bottom-up priming of top-down attentional control settings. *Visual Cognition*, **16**, 215-231.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception & Performance*, **18**, 1030-1044.

Folk, C. L., Remington, R. W., & Wright, J. H. (1994). The structure of attentional control: Contingent attentional capture by apparent motion, abrupt onset, and color. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 317-329.

JONIDES, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In J. [B.] Long & A. [D.] Baddeley (Eds.), *Attention and performance IX* (pp. 187-203). Hillsdale, NJ: Erlbaum.
LAMY, D., LEBER, A. [B.], & EGETH, H. E. (2004). Effects of task relevance and stimulus-driven salience in feature-search mode. *Journal of Experimental Psychology: Human Perception & Performance*, **30**, 1019-1031.
POSNER, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, **32**, 3-25.
THEEUWES, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics*, **51**, 599-606.
YANTIS, S., & JONIDES, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. *Journal of Experimental Psychology: Human Perception & Performance*, **10**, 601-621.

(Manuscript received August 25, 2009;
revision accepted for publication January 1, 2010.)