1 Probability manipulations can modulate but not reverse reflective inhibition-of-return effects

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Abstract

Inhibition of return (IOR) is a phenomenon of perceptual attention characterized by delayed shifts in attention toward previously cued target locations. In reflective (internally directed) attention studies, response times (RTs) to cued items are sometimes facilitated, but other times IOR-like effects are observed wherein RTs to probed items are slower when the items had been mentally attended (refreshed) earlier in the trial. Perceptual IOR is known to be modulated by the probability that target and cued locations match. If the same is true for reflective attention, it could account for why sometimes reflective attention can lead to facilitation and other times inhibition. In the current study, four experiments examined the potential facilitative or inhibitory influence of probe predictability in reflective attention. We first replicated the design and IOR-like pattern of results originally reported by Johnson et al. (2013). In subsequent experiments, when the proportion of unrefreshed probes was increased, the IOR-like effect increased in magnitude. When the proportion of refreshed probes was increased, the IOR-like effect was eliminated, but there was no evidence for facilitation. Altogether, these results are consistent with perceptual IOR literature implicating underlying inhibitory and facilitative attentional processes that can either interact synergistically or nullify each other. Further work will be needed to fully understand the paradoxical effects of why reflective attention is sometimes inhibitory and other times facilitative, but the current results demonstrate that expectation can play a significant role in the size of the effect.

Keywords: attention, working memory, inhibition of return, refreshing

Introduction

In the visual domain, attention is a critical cognitive mechanism for enhancing the processing of information at a specific location at the expense of decreased processing at unattended locations (Bashinski & Bacharach, 1980; Posner, 1980). However, it is not generally adaptive behavior for attention to remain fixated in one location indefinitely or, in a visual search context, to repeatedly resample a portion of the environment in which the search target was previously found to be absent. Inhibition of return (IOR; Posner & Cohen, 1984; for review, see Klein, 2000) is one mechanism that enables efficient visual search by discouraging shifts of attention to previously attended locations. In a classic IOR task, participants maintain central fixation and see an exogenous attention cue presented either left or right of fixation, followed by a target at one of those locations. The time delay between cue and target onset can be varied; at shorter delays ($< \sim 300\text{ms}$), target responses are typically enhanced (faster) at cued locations relative to uncued locations. However, at delays greater than $\sim 300\text{ms}$, the effect is reversed; participants respond faster to targets shown at uncued locations. Although many variations on IOR tasks and effects exist, the typical interpretation of the basic effect is that attention naturally “wants” to rove: Shortly after being drawn to a location, the focus of attention tends to shift to a new location and is temporarily inhibited from returning to the old location, hence the name of the effect.

Of course, attention is not a purely sensory phenomenon; it can also be directed internally to specific representations in working memory (WM). Analogous to the enhancement of processing for attended visual targets, participants are generally faster to respond to probes of attended representations in WM than to those that are unattended (Astle, Summerfield, Griffin, & Nobre, 2012; Griffin & Nobre, 2003; Lepsien & Nobre, 2006). This process of directing reflective attention to an item in WM, thus foregrounding it relative to other concurrently maintained items, is sometimes termed “refreshing” (Johnson & Hirst, 1993; Raye, Johnson, Mitchell, Greene, & Johnson, 2007; see also Camos et al., 2018). To

prompt a refresh operation experimentally, it is typically necessary to use a retro-cue rather than the pre-cues used in most visual attention studies; however, despite this temporal reversal, perceptual and reflective attention have much in common. For instance, they are subserved by a similar network of brain regions, and they have similar modulatory effects on activity in category-specific visual brain areas corresponding to attended or unattended items (Chun & Johnson, 2011; Johnson & Johnson, 2009; Johnson, Mitchell, Raye, D’Esposito, & Johnson, 2007).

In one particularly striking similarity between reflective and perceptual attention, Johnson et al. (2013) observed an IOR-like response pattern in a reflective attention task. Participants in that study viewed pairs of items, followed by a retro-cue instructing them to refresh one item, and finally a probe that was equally likely to be the refreshed item, the unrefreshed item (shown initially but not cued for refreshing), or a novel item (not previously used in the task). As expected, participants were slowest to respond to novel probes, as they had not previously encountered them in the experiment. However, rather than demonstrating the anticipated facilitatory effect of retro-cueing in which participants respond faster to probes of the refreshed item than the unrefreshed item(s), the opposite was observed. This pattern of results mimics that of IOR in the perceptual domain; attention was directed to a WM representation, and responses to subsequent probes of that item were seemingly inhibited. This effect is hereafter referred to as reflective IOR (rIOR).

It is currently unclear why retro-cues sometimes evoke enhanced response times (RTs) to refreshed items and other times produce IOR-like effects. The IOR literature suggests that shorter delays between refresh cues and probes might facilitate RTs, but this does not match the timing parameters of the retro-cue literature, and our previous attempts to elicit facilitation with shorter delays were unsuccessful (Poh, 2017). Higgins, Johnson, and Johnson (2020) did find that the rIOR was eliminated in older adults with the timing used by Johnson et al. (2013) and restored using a longer delay, but actual facilitation was never

observed. Other retro-cue studies have varied widely in their parameters, but a recent study of ours (Lintz & Johnson, 2020, Experiment 2) found refreshing-induced facilitation with a design very close to that of Johnson et al. (2013). Between these two studies, there were only three noteworthy differences, significantly narrowing the possible set of explanations: Johnson and colleagues recorded *verbal* responses to *randomly probed* items from an initially presented *set of two*, whereas Lintz and Johnson (Experiment 2) recorded *keypresses* to probes from an initial *set of three* items but with *mostly refreshed probes* (80% cue validity).

The IOR effect in visual attention has been reliably demonstrated despite manipulations of response modality (Taylor & Klein, 2000) and the number of possible target locations (Posner & Cohen, 1984), thus leaving cue validity (i.e., probe type probability) as the prime candidate for modulating the effect in reflective attention. Additionally, perceptual IOR has been shown to be moderated by cue validity (Lim, Eng, Osborne, Janssen, & Satel, 2019; López-Ramón, Chica, Bartolomeo, & Lupiáñez, 2011; Wright & Richard, 2000). When pre-cues are uninformative, as in Posner and Cohen (1984), IOR is observed; however, when cues begin to predict subsequent probes, the magnitude of the IOR effect is diminished. At cue validities approaching Lintz & Johnson’s study, the IOR effect is eliminated. Thus, the current study seeks to replicate the IOR-like effects found by Johnson et al. (2013) and test whether cue validity mediates facilitatory versus inhibitory effects by varying the relative probabilities of different probe types (refreshed, unrefreshed, or novel).

Methods

Participants

All of the materials and procedures used in these experiments were approved by the University of Nebraska-Lincoln Institutional Review Board prior to the recruitment of participants. All procedures were in accord with the 1964 Declaration of Helsinki. Upon arrival, participants were randomly assigned to one of the four experiments, which were conducted concurrently: Experiment 1: Equiprobable, Experiment 2: Novel Probable,

Experiment 3: Unrefreshed Probable, Experiment 4: Refreshed Probable. Participants were blind to their assigned experiment, and indeed were unaware of the existence of other experiment versions until the post-experiment debriefing. No individual participated in more than one of the experiments. All participants were undergraduates who participated in exchange for course credit.

An a-priori power analysis calculated using G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007) revealed that $N = 6$ participants for each experiment would be necessary to detect the smallest rIOR effect reported by Johnson and colleagues (2013; $\eta_p^2 = 0.66$) with a power of $\alpha = .95$. A total of 31 participants (female $n = 24$, male $n = 7$) between ages 18 and 32 ($M = 19.57$, $SD = 2.61$) completed one of the four experiments. Prior to analysis, the data for one participant from Experiment 1 and one participant in Experiment 4 were removed due to poor enunciation that made it difficult to score the recordings for accuracy. The participant demographics for each experiment are presented in Table 1.

Table 1
Demographic Information

Experiment	N		Age	
	Female	Male	Mean	SD
Experiment 1	7	0	18.86	0.90
Experiment 2	7	2	19.00	1.20
Experiment 3	6	2	19.75	1.28
Experiment 4	4	3	20.71	5.09

Procedure

At the beginning of the session, participants were reminded that the task used verbal responses, that their voices would thus be recorded, and that there would be no penalty if they chose not to continue with the experiment. After the participant consented to continue, the researcher read the task instructions out loud to them. If the participant had any questions, those were addressed, and then three practice trials were completed (one of each trial type; see below). Following the practice trials, the researcher provided feedback on

performance and addressed any issues or mistakes. In some cases, the practice trials were repeated to ensure that participants were comfortable with the task before moving on to the experiment.

Before the start of each block, the researcher started the audio recording, then initiated the task. At the beginning of each task block, three loud beeps were played, which allowed us to synchronize the task's own event timestamps with the audio recording. Responses were recorded using a Sony ICD-PX 370 digital recorder, which was mounted on a small desktop microphone stand placed in front of the participant. At the end of each block, the audio recording was stopped and the participant was given time to rest. When the participant was ready to continue, the same procedure was repeated. When the task was over, the participants completed a demographics survey and were then debriefed and thanked for their participation.

Design and Materials

The experiments were programmed and presented using Psychtoolbox (Brainard, 1997) in MATLAB 2015b (The MathWorks, Natick, MA). All four experiments followed the same trial structure and used the same materials. The stimuli were presented on a 1920 x 1080 resolution monitor at a natural desktop viewing distance. Word stimuli were printed in 96pt white Arial font on top of a neutral gray background.

Task. As with Johnson et al. (2013), each trial started with two words presented simultaneously in the top and bottom halves of the monitor (1,500 ms), which participants were instructed to read silently (see Figure 1). The initially presented words were followed by a blank inter-stimulus interval (ISI; 500 ms), and then an arrow pointing in the direction of one of the previously presented words (1,500 ms) cueing the participants to refresh the indicated item (think back to the word in the location indicated and speak it out loud as quickly and accurately as possible). Next came a brief (100 ms) blank ISI followed by a probe word (1,500 ms) that participants were instructed to read out loud as quickly and

accurately as possible. The task contained three different trial types: Refreshed Probe, Unrefreshed Probe, Novel Probe. For Refreshed Probe trials, the probe word matched the word that had just been cued by the arrow and refreshed aloud. For Unrefreshed Probe trials, the probe word matched the word that was initially presented at the start of the trial, but not refreshed. For Novel Probe trials, the probe word was a completely new word that had not been previously presented to the participants. The inter-trial interval was 3,000 ms.

Figure 1. Trial types were defined by the cue-probe relationship. For Refreshed Probe trials, the probe word matched the cued word. For Unrefreshed Probe trials, the probe word matched the word that was initially presented but not cued. For Novel Probe trials, the probe word was a new word.

The task consisted of 144 trials presented in four blocks of 36 trials apiece. Each experiment differed in the proportion of trials assigned to each trial type. For the Equiprobable experiment, each trial type was presented an equal number of times (33.3%; 48 trials per trial type total, 12 trials per trial type per block). In the other three experiments, the most probable trial type for each experiment made up 66.7% of the trials for that experiment (96 trials total, 24 trials per block), and the less probable trial types each made up 16.7% of the trials (24 trials total, 6 trials per block). Within each block, the trial order was pseudo-randomized, with the constraint that the same trial type was never presented more than three times in a row.

Word Lists. Separate word lists were used for the practice and experimental trials. The words from the practice word list were presented in the same order for every participant. The word list for the experimental trials consisted of 432 common two-syllable nouns. For each participant, the word stimuli used in the main task were randomly drawn from this

pool, without replacement.

Data Processing

A custom MATLAB script (originally developed by Johnson et al., 2013) was used to process the audio recordings and detect the onset of the verbal response (i.e., response time). The audio recordings were high-pass filtered (100 Hz threshold) prior to processing. The processing script paired words from the ordered wordlist with each sound that was detected. The researcher listened to each word detected by the script to confirm that the correct word was spoken. The script allowed for onset times to be manually adjusted for precision, and for extraneously detected sounds to be removed from the analysis (for more details, see Johnson et al., 2013). To avoid experimenter bias, the researchers were blind to the experiment assigned to the participants while running the sessions and processing the audio recording data.

Prior to analysis, trials containing ambiguous or incorrect responses to the cue or probe were removed, as well as outliers. A total of 325 trials (7.3% of trials) were removed because the response to the cue or probe word was incorrect or inaudible. Because our hypotheses were centered around the consequences of our manipulations for the probe RTs, all subsequent analysis focused on probe responses. For each participant's probe responses, we also trimmed outliers; probe responses with RTs greater than three standard deviations from the participant's mean probe RT were removed. After this, the trimmed data were re-assessed for any new outliers that emerged, and the process was repeated recursively until no outliers were detected. In total, 108 responses (2.4% of the data) were labeled as outliers and removed.

Results

The means and standard deviations for each condition are presented in Table 2. For each experiment, a one-way repeated-measures Analysis of Variance (ANOVA) was used to

evaluate the effect of trial type (see Table 3). In all four experiments, the one-way repeated-measures ANOVA was significant (all p 's < .001). Holm's method was used to correct for multiple within-subjects contrasts.

Table 2
Descriptive Statistics

Experiment	Refreshed Probe		Unrefreshed Probe		Novel Probe	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Experiment 1: Equiprobable	503	35	479	29	545	21
Experiment 2: Novel Probable	559	77	519	74	572	79
Experiment 3: Unrefreshed Probable	536	107	471	102	580	136
Experiment 4: Refreshed Probable	547	127	544	114	588	119

Table 3
Omnibus Comparisons by Experiment

Experiment	df_1	df_2	F	p	η^2
Experiment 1: Equiprobable	2	12	28.257	< .001	0.825
Experiment 2: Novel Probable	2	16	27.979	< .001	0.778
Experiment 3: Unrefreshed Probable	2	14	34.837	< .001	0.833
Experiment 4: Refreshed Probable	2	12	14.878	< .001	0.713

Experiment 1: Equiprobable

In Experiment 1 (Figure 2a), where all probe types were equally probable, refreshed probes ($t_6 = 4.082$, $p_{Holm} = 0.013$) and unrefreshed probes ($t_6 = 8.695$, $p_{Holm} < .001$) had shorter RTs than novel probes, demonstrating the expected priming effect (both refreshed probes and unrefreshed probes were seen earlier in the trial, whereas novel probes were not). More critically, RTs to refreshed probes were slower than to unrefreshed probes ($t_6 = 2.818$, $p_{Holm} = 0.030$). Overall, these results replicate the rIOR effect described by Johnson et al. (2013).

Experiment 2: Novel Probable

In Experiment 2 (Figure 2b), where novel probes were most probable, RTs to probe words were numerically slower than in Experiment 1 for all probe types (but not significantly; see below). Still, the rIOR effect remained intact; RTs to refreshed probes were slower than

Figure 2. Response time results for all four experiments. The graphs show response time as a function of the trial type. Experiment 1 (a) represents a replication of the original rIOR paradigm established by Johnson et al. (2013). Experiment 2 (b) modified the original rIOR design so the probe was a novel word for 66.7% of the trials. Experiment 3 (c) modified the original rIOR design so the unrefreshed word was probed on 66.7% of trials. Experiment 4 (d) modified the the original rIOR design so the refreshed word was probed on 66.7% of trials. The error bars for all of the plots were calculated using standard errors that were adjusted for repeated measures (Morey, 2008).

to unrefreshed probes ($t_8 = 5.239$, $p_{Holm} < .01$). Novel probe RTs were also slower than unrefreshed probe RTs ($t_8 = 9.097$, $p_{Holm} < .001$). However, refreshed probe RTs did not differ from novel probe RTs, even without a multiple-comparisons correction ($p_{Uncorrected} = 0.162$). Thus, although the increased frequency did not make participants respond faster to novel probes than to either of the other two probe types, and in fact participants responded numerically slower to all probe types in Experiment 2 versus Experiment 1, the probability manipulation did attenuate the priming benefit of refreshing probes.

Experiment 3: Unrefreshed Probable

In Experiment 3 (Figure 2c), where unrefreshed probes were most probable, both refreshed probes ($t_7 = 3.485$, $p_{Holm} < .01$) and unrefreshed probes ($t_7 = 6.819$, $p_{Holm} < .001$) again had shorter RTs than novel probes, and refreshed probe RTs were again slower than those of unrefreshed probes ($t_7 = 6.426$, $p_{Holm} < .001$). This qualitatively matches the pattern observed in Experiment 1, although the rIOR appeared to be amplified in Experiment 3 (see the between-experiment comparisons below).

Experiment 4: Refreshed Probable

In Experiment 4 (Figure 2d), where refreshed probes were most probable, both refreshed probes ($t_6 = 3.603$, $p_{Holm} = 0.023$) and unrefreshed probes ($t_6 = 8.626$, $p_{Holm} < .001$) again had shorter RTs than novel probes. However, RTs to refreshed and unrefreshed probes did not differ, even without a multiple-comparisons correction ($p_{Uncorrected} = 0.774$). Thus, although the priming benefit relative to novel probes remained intact, the increased frequency of refreshed probes appeared to eliminate the rIOR effect.

Between-experiment Comparisons

To follow up on the results from the individual experiments, we compared them with a 4 (between-subjects: probability group) x 3 (within-subjects: probe type) mixed ANOVA. There was no main effect of group ($F_{3,27} = 0.443$, $p = 0.724$, $\eta_p^2 = 0.047$), but there was a main effect of probe type ($F_{2,54} = 94.460$, $p < .001$, $\eta_p^2 = 0.778$), and an interaction of group and probe type ($F_{6,54} = 5.997$, $p < .001$, $\eta_p^2 = 0.400$). Of those, the interaction was of primary interest, insofar as it might reflect differences in the rIOR effect among probability groups.

To assess differences in rIOR among the probability groups, four follow-up post-hoc independent-samples t -tests were conducted to compare differences in RT between the Refreshed Probe and Unrefreshed Probe trial types for each experiment. Holm's method was

used to adjust all p -values. The critical comparisons were comparing each of Experiments 2-4 to the baseline Experiment 1, as well as an additional comparison between Experiments 3 and 4. Experiment 1 (Equiprobable) did not differ from Experiment 2 (Novel Probable; $t_{14} = 1.288$, $p_{Holm} = 0.222$, $d = 0.649$) or Experiment 4 (Refreshed Probable; $t_{12} = 1.722$, $p_{Holm} = 0.222$, $d = 0.920$), but it did differ from Experiment 3 (Unrefreshed Probable; $t_{13} = 2.944$, $p_{Holm} = 0.034$, $d = 1.524$). In addition, Experiments 3 and 4 differed from each other ($t_{13} = 4.478$, $p_{Holm} < .01$, $d = 2.317$).

Discussion

The findings from these four experiments provide further evidence for an rIOR effect that is analogous, but not identical, to the perceptual IOR originally reported by Posner and Cohen (1984). For Experiment 1 (Equiprobable), there was an RT advantage for primed words (versus novel probes), but the advantage was less for words that were explicitly refreshed immediately prior to being probed. This outcome replicated the IOR-like pattern of results originally reported by Johnson et al. (2013), who showed a facilitative effect (shorter RTs) to probe words and images recently encoded in working memory, but an inhibitory effect of refreshing these items immediately prior to the probe (i.e., rIOR).

In perceptual IOR studies, RTs to high-probability probes are typically shorter than to low-probability probes (López-Ramón et al., 2011; Wright & Richard, 2000). The facilitative effects associated with predictable probes have been attributed to goal-directed attentional processes that occur in response to some level of awareness of the probability relationship between the cues and the probes (López-Ramón et al., 2011; Wright & Richard, 2000). Recent research from our group (Lintz & Johnson, 2020) has prompted the hypothesis that rIOR is also modulated by probe type probability.

In Experiment 2 (Novel Probable) of the current study, probes were most likely to be a non-primed word. Somewhat contrary to expectations, the high probability of novel probes

275 did not facilitate RTs to them relative to Experiment 1; in fact, Experiment 2 had
276 (non-significantly) slower RTs for all trial types (see Figure 2). Of course, because the
277 probable probes were novel (previously unseen) words, by definition the cues could not be
278 explicitly predictive of the *specific* probe word. This stands in contrast to previous studies
279 (and Experiments 3-4 of this study), in which probe predictability referred to specific
280 items/locations, and likely explains the lack of novel-probe facilitation and possible overall
281 slowing relative to Experiment 1. However, Experiment 2 did eliminate any differences
282 between refreshed and novel probes, so in some sense, it could be said that the high
283 novel-probe probability did somewhat facilitate novel probes (i.e., eliminated some priming
284 benefits) relative to the other conditions in Experiment 2. Regardless, more relevant to the
285 primary motivations for the current study, the high novel-probe probability of Experiment 2
286 did not change the relationship between refreshed and unrefreshed probe RTs (i.e., the rIOR
287 effect), relative to Experiment 1.

288 In Experiment 3, the high probability of unrefreshed probes would be expected to
289 engage (perhaps implicit) goal-directed attention towards unrefreshed items and away from
290 refreshed items during the brief interval between the refresh cue and probe, which in turn
291 should be expected to work synergistically with the “default” rIOR effect seen in Experiment
292 1. This hypothesis was indeed confirmed, with high unrefreshed probe probability producing
293 (relative to Experiment 1) numerically slower RTs to refreshed probes, numerically faster RTs
294 to unrefreshed probes, and overall a significantly greater rIOR effect (see Figure 2).
295 Although we are not aware of a direct parallel in the perceptual IOR literature (but see
296 López-Ramón et al., 2011), our finding is generally in line with Wright and Richard’s (2000)
297 proposition that expectation effects combine more-or-less additively with IOR effects. The
298 most critical question, however, was whether probability manipulations could neutralize or
299 even reverse rIOR effects, which we tested in Experiment 4.

300 In contrast to Experiment 3, the IOR-like inhibitory and expectation-driven facilitative

processes were pitted against each other during Experiment 4 (Refreshed Probable). The high probability of refreshed probes encouraged participants to maintain the focus of mental attention on the refreshed item after the offset of the cue, thus acting in opposition to the putatively automatic rIOR effect. In line with these expectations, we found that rIOR was eliminated (see Figure 2). Although our between-experiments analysis found no significant main effect of probability group, Experiment 4 did have numerically slower RTs than Experiment 1 for all probe types, hinting at the possibility that the conflict between inhibitory and facilitative processes produced higher cognitive load. The nullification of rIOR effectively replicates the perceptual IOR results of Wright and Richard (2000) in the reflective domain; however, the high probability of refreshed probes was not sufficient here to flip the effect from inhibitory to facilitative, as observed by Lintz and Johnson (2020) and other studies using reflective attention retro-cues.

Altogether, these findings support previous research (Johnson et al., 2013) indicating that focusing mental attention on an item in working memory can have downstream effects on the item's processing that mirror the consequences of perceptual attention, and specifically that the putatively automatic rIOR effect can be either magnified or eliminated by manipulations of probe probability (and thus participants' expectations). Although a notable result in itself, this finding leaves open the question of why other retro-cue studies find clear facilitation for the cued item. Compared to our own previous work (Lintz & Johnson, 2020), the primary remaining alternatives concern the number of items in the initial set (two versus three) or the use of explicit verbal responses for refreshing and probe (present study) versus silent (internal) refreshing and a button-press response (word/nonword judgment) by Lintz & Johnson. As many other studies of refreshing have used set sizes between one and three items in the initial set without finding drastic behavioral or neural differences based on set size, the more promising candidate is likely the modality of refreshing and/or the probe. If such modality is indeed revealed to be the driving factor, that could have important implications for understanding the nature of reflective attention;

for example, it may well be that rIOR is primarily a sensorimotor phenomenon that does not penetrate to the semantic level of an item's mental representation. This hypothesis would be tentatively supported by previous preliminary data in bilinguals indicating that the rIOR phenomenon occurs when refreshing and probe are performed in the same language, but facilitation of the refreshed item is observed when the probe is a phonetically distinct translation of the item into another language spoken by the participant (Poh, 2017). However, it remains the task of future work to confirm this hypothesis more conclusively.

Declarations

Open Practices

The data and materials are available upon request from the corresponding author. None of the experiments were preregistered.

Conflict of Interests

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The authors declare they have no financial interests.

Ethics Approval

All of the materials and procedures used in these experiments were approved by the University of Nebraska-Lincoln Institutional Review Board prior to the recruitment of participants. All procedures were in accord with the 1964 Declaration of Helsinki.

351 **Consent to Participate**

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

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