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The Flexible Focus: Whether Spatial Attention Is Unitary or Divided Depends on Observer Goals

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The distribution of visual attention has been the topic of much investigation, and various theories have posited that attention is allocated either as a single unitary focus or as multiple independent foci. In the present experiment, we demonstrate that attention can be flexibly deployed as either a unitary or a divided focus in the same experimental task, depending on the observer's goals. To assess the distribution of attention, we used a dual-stream Attentional Blink (AB) paradigm and 2 target pairs. One component of the AB, Lag-1 sparing, occurs only if the second target pair appears within the focus of attention. By varying whether the first-target-pair could be expected in a predictable location (always in-stream) or not (unpredictably in-stream or between-streams), observers were encouraged to deploy a divided or a unitary focus, respectively. When the second-target-pair appeared between the streams, Lag-1 sparing occurred for the Unpredictable group (consistent with a unitary focus) but not for the Predictable group (consistent with a divided focus). Thus, diametrically different outcomes occurred for physically identical displays, depending on the expectations of the observer about where spatial attention would be required.

Keywords: visual attention, spatial attention, attentional blink, divided attention, expectation

Stimuli presented at attended locations are processed faster and more accurately than those presented at unattended locations (LaBerge, 1995). Theories to account for this benefit typically appeal to either (a) a single unitary focus of attention that expands and contracts so as to optimize performance on the task at hand (e.g., Barriopedro & Botella, 1998; Castiello & Umiltà, 1990, 1992; Eriksen & St. James, 1986; Eriksen & Yeh, 1985; Heinze et al., 1994; Jans, Peters, & De Weerd, 2010; Jonides, 1983), or (b) multiple foci deployed to different locations simultaneously (e.g., Awh & Pashler, 2000; Cave, Bush, & Taylor, 2010; Kawahara & Yamada, 2007; McMains & Somers, 2004, 2005; Müller et al., 2003). Here we demonstrate that focused attention can be flexibly deployed in either a unitary or a divided mode. Specifically, our goal was to show that both modes of attentional deployment can occur when viewing the same stimulus displays, and that whether spatial attention is unitary or divided will depend on the expectations of the observer.

To allow both types of attentional deployment to be assessed with the same experimental procedure, we modified two well-established behavioral measures of attention: the attentional blink and Lag-1 sparing. The attentional blink (AB) refers to the impaired identification of the second of two rapidly sequential targets (T1, T2). This deficit is most pronounced at short intertarget lags, and vanishes at lags beyond about 500 ms (Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992). Lag-1 sparing refers to the somewhat paradoxical finding that identification of the second target is unimpaired when it appears directly after the first target in the same spatial location (Potter, Chun, Banks, & Muckenhoupt, 1998; Visser et al., 1999). It is defined as the difference in second-target identification accuracy at Lag 1 and at the lowest following lag (e.g., Lag 3; Potter, Chun, Banks, & Muckenhoupt, 1998). It has been shown that Lag-1 sparing also occurs to targets in different spatial locations, but only if T2 falls within the focus of attention (Jefferies & Di Lollo, 2009; Jefferies, Ghorashi, Kawahara, & Di Lollo, 2007; Shih, 2000). The incidence of Lag-1 sparing can, therefore, be used to determine whether or not a particular spatial location falls within the focus of attention and thus to assess the distribution of attention across space (Jefferies & Di Lollo, 2009; Jefferies, Ghorashi, Kawahara, & Di Lollo, 2007; Kawahara & Yamada, 2007; Lunau & Olivers, 2010).

Our implementation of the AB and Lag-1 sparing was based on the methodology used by Kawahara and Yamada (2007),

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who used two concurrent streams of digit distractors, one on either side of fixation, separated by a spatial gap. A first pair of letter targets (T1-pair) appeared simultaneously, one in each stream (*in-stream* condition). A second pair of letter targets (T2-pair) appeared either in-stream or in the spatial gap between the streams (between-streams condition). In that experiment, Lag-1 sparing occurred when the T2-pair appeared in-stream, but not when it appeared between-streams. Kawahara and Yamada concluded that the space between the streams was unattended and, therefore, that focal attention could be split between two discontinuous locations.

Here we test whether focal attention can be deployed flexibly in a unitary or divided mode depending on the observer's expectations about where attention will need to be deployed to optimize task performance. On this view, Kawahara and Yamada's (2007) results stemmed from the fact that the T1-pair always appeared in-stream. If attention is initially deployed so as to optimize T1-pair identification (the first portion of the experimental task; Dubois, Hamker, & Van Rullen, 2009; Jefferies & Di Lollo, 2009), then the T1-pair appearing consistently in-stream would encourage observers to divide attention and deploy one focus to each stream. In the present study we used two different conditions to encourage observers to adopt either a unitary or a divided focus of attention. In one condition (*T1-Pair Predictable*), the T1-pair always appeared in-stream, as in Kawahara and Yamada's study, encouraging the deployment of two separate attentional foci. The other condition (*T1-Pair Unpredictable*) was designed to encourage the deployment of a single broad attentional focus that encompassed all potential target locations. To that end, we presented the T1-pair unpredictably either in-stream or in the space between the streams (see Figure 1 insets).

It is important to note that the labels Predictable and Unpredictable apply only to the location of the T1-pair. In both conditions, the T2-pair appeared randomly and with equal probability either in-stream or between-streams. The trials of interest are those in which the T2-pair appeared between-streams because the deployment of attention to the space between the streams depends on whether the focus of attention is unitary or divided: if focal attention is unitary, the central region will be attended, and Lag-1 sparing will occur to T2-pairs presented in that region. If, on the other hand, attention is divided into two separate foci, the central region will be unattended, and Lag-1 sparing will not occur.

In brief, we expected to replicate Kawahara and Yamada's (2007) findings in the T1-pair predictable condition (i.e., no Lag-1 sparing when the T2-pair appears between the streams), but to find

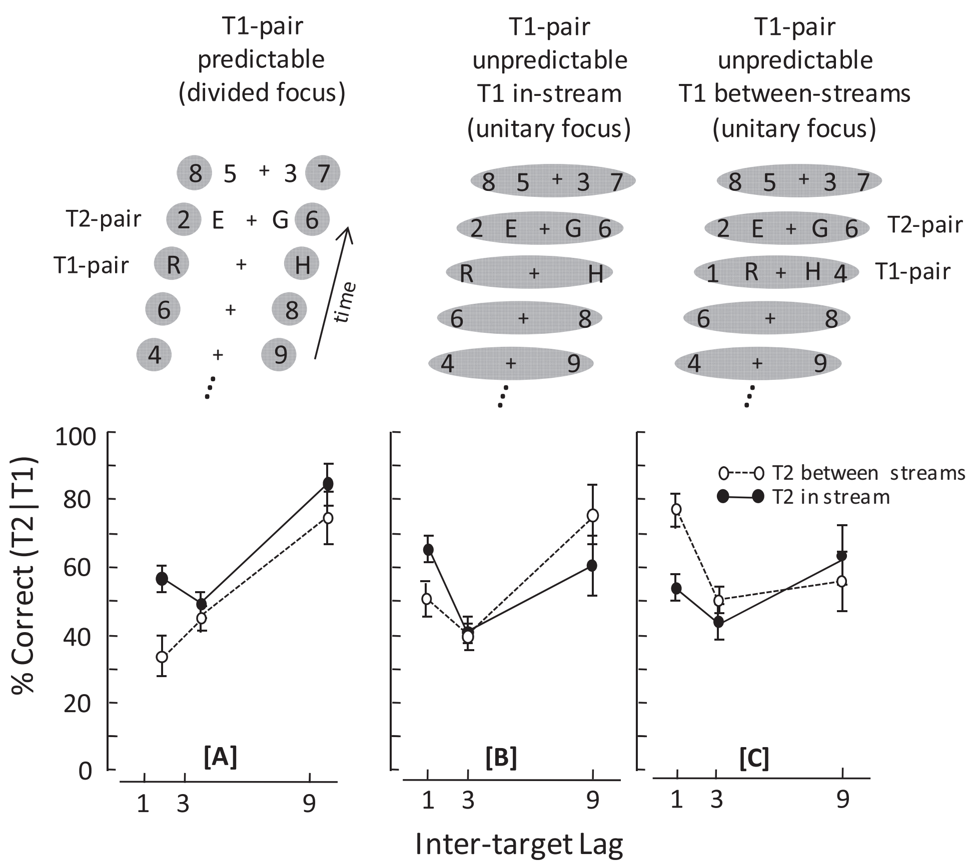

Figure 1. Mean percentage of correct responses for the T2-pair. Insets illustrate the display sequences at Lag 1. A: T1-pair Predictable, B: T1-pair Unpredictable (trials in which T1-pair appeared in-stream), C: T1-pair Unpredictable (trials in which T1-pair appeared between-streams). The shaded areas represent the hypothesized spatial distribution of focal attention.

substantial Lag-1 sparing in the unpredictable condition. Such a pattern of results would suggest that focal attention is divided when the location of the T1-pair is predictable and unitary when it is unpredictable.

Method

Participants

Twenty-six Simon Fraser University undergraduates (16 females, ages 19–24) were randomly allocated to two groups: Fifteen in the T1-Pair Predictable and 11 in the T1-Pair Unpredictable group. All had normal or corrected-to-normal vision and were naïve as to the purpose of the experiment.

Stimuli and Procedure

Observers made three responses on each trial: the first response was to indicate whether the T1-pair letters were the same or different from one another; the second and third responses were to identify both letters in the T2-pair.

Stimuli were displayed on a 75-Hz computer monitor viewed from approximately 60 cm. Stimulus and background luminance was 129 and 2.3 cd/m^2, respectively. A white fixation cross was displayed centrally. Two synchronized rapid serial visual presentation (RSVP) streams of stimuli were presented 1.75° to either side of fixation (center-to-center). Each stream contained 8–14 randomly chosen leading white digit-distractors (~0.9° in height), appearing one every 100 ms. Each stimulus was displayed for 70 ms, followed by a blank interval of 30 ms. The digits were selected randomly with replacement from the set 1–9, with the restrictions that the same digit could not appear in both streams simultaneously and that the same digit could not appear in two sequential frames. The targets were two pairs of white letters from the English alphabet, excluding I, O, Q, and Z. The letters in the T1-pair were the same as one another on half the trials, and different from one another on the remaining trials. The two trial types were intermixed randomly. The letters in the T2-pair always differed from one another.

For one group of observers (T1-pair Predictable group), the T1-pair was always presented in-stream. For the other group (T1-pair Unpredictable group), the T1-pair was presented with equal probability either in-stream or in the space between the streams, randomly. For both groups, the T2-pair could appear either in-stream or between-streams and could therefore appear either in the same location as the T1-pair or in a different location (see Figure 1 insets). As noted above, the latter is the condition of interest because it permits an assessment of the spatial extent of focal attention.

The T2-pair followed the T1-pair at one of three intertarget lags: Lag 1 (100 ms; the T2-pair was presented directly after the T1-pair), Lag 3 (300 ms; two distractors intervened the target-pairs), and Lag 9 (900 ms; eight distractors intervened the target-pairs). The three lags occurred randomly with equal frequency across trials. Each target was masked by a trailing digit except when the T2-pair followed directly after the T1-pair (Lag 1) in the same location, in which case the T2-pair masked the T1-pair. The total number of trials in both conditions was 384.

Results

Accuracy of T1-pair responses are as follows: T1-pair Predictable group, 68%, 67%, and 71% at Lags 1, 3, and 9, respectively; T1-pair Unpredictable group, T1-pair between-streams, 72%, 74%, and 68% at Lags 1, 3, and 9, respectively; T1-pair Unpredictable group, T1-pair in-stream, 74%, 71%, and 82%, at Lags 1, 3, and 9, respectively. Only trials in which the response to the T1-pair was correct were included for analysis.[1]

Figure 1 illustrates the percentage of correct T2-pair responses for the T1-pair Predictable (panel A) and T1-pair Unpredictable conditions (panels B and C). Of particular importance are the data for T2 between-streams (open circles). If Lag-1 sparing is evident in those data, this indicates that the central region was attended, consistent with a unitary focus of attention. If no Lag-1 sparing is in evidence, it can be inferred that the central region was unattended and that the focus of attention was divided. The results are unambiguous: robust Lag-1 sparing is in evidence when the T1-pair is unpredictable, but there is no hint of Lag-1 sparing when the T1-pair is predictable. These observations were supported by the following statistical analyses.

Because the measure of interest was Lag-1 sparing, all analyses were limited to the data for Lags 1 and 3. Lag 9 was of no theoretical interest and was included in the experiment to (a) make the appearance of the T2-pair less temporally predictable, and (b) confirm that an AB occurred. We calculated the magnitude of Lag-1 sparing as the positive difference between T2-pair accuracy at Lag 1 and Lag 3. A negative difference was termed *Lag-1 deficit*.

Because the data in Figure 1 cannot form a complete factorial design, we performed two separate analyses: one for the T1-pair Predictable group, the other for the T1-pair Unpredictable group. This was followed by a third analysis on the data in Figures 1A and 1B, which represent matching conditions in the T1-pair Predictable and T1-pair Unpredictable conditions. In both of these conditions, the T1-pair was presented in-stream, with the T2-pair presented either in-stream or between-streams. This analysis is the most direct test of the prediction that the focus of attention is unitary in the T1-pair Unpredictable condition, but divided in the T1-pair Predictable condition.

The first analysis was a 2 (Lag:1, 3) × 2 (T2-pair Location: in-stream, between-streams) within-subject ANOVA for the T1-pair Predictable group (Figure 1A). The analysis revealed a significant effect of T2-pair location, $F(1, 14) = 14.02$, $p = .002$, $\eta^2 = .50$, and a significant Lag × T2-Pair Location interaction, $F(1, 14) = 4.85$, $p = .045$, $\eta^2 = .257$. No other effects were significant. This pattern of results indicates that when the location of the T1-pair was predictable, attention was divided into two separate foci, leaving the central region unattended. If the T2-pair then appeared in that central region, Lag-1 deficit ensued. In contrast, if the T2-pair appeared in-stream, Lag-1 sparing was in

[1] This procedure is commonly adopted on the grounds that, on trials in which T1 is identified incorrectly, the source of the error is unknown, and thus its effect on T2-processing cannot be estimated. The two responses to the target pairs were scored independently of the order in which they were reported, and the two responses to the T2-pair were averaged to calculate a single T2-pair score, following Kawahara and Yamada (2007).

evidence. As expected, these results replicate those of Kawahara and Yamada (2007).

The second analysis was a 2 (Lag: 1, 3) × 2 (T1-pair Location: In-stream, between-streams) × 2 (T2-pair location: In-stream, between-streams) within-subject ANOVA for the T1-pair Unpredictable group (Figure 1B and 1C). The analysis revealed a significant effect of T2-pair location, $F(1, 10) = 7.17$, $p = .023$, $\eta^2 = .42$, and a significant Lag × T2-Pair Location interaction, $F(1, 10) = 5.75$, $p = .037$, $\eta^2 = .37$. No other effects were significant. The finding that Lag-1 sparing occurred when the T2-pair was presented between the streams indicates that the region between the two streams was encompassed within the focus of attention. This, in turn, strongly suggests that, when the location of the T1-pair was unpredictable, attention was deployed as a single unitary focus.

The third analysis, the most direct test of our hypothesis, compared the two segmented lines for Lags 1 and 3 in Figures 1A and 1B. These data are for the conditions in which the T2-pair appeared in the region between the streams. According to the rationale outlined in the Introduction, the occurrence of Lag-1 sparing (Figure 1B, segmented line) is indicative of a unitary focus of attention, whereas the occurrence of Lag-1 deficit (Figure 1A, segmented line) is indicative of a divided focus of attention. This means that the focus of attention was divided in the T1-pair Predictable condition (Figure 1A, replicating Kawahara & Yamada, 2007) but was unitary in the T1-pair Unpredictable condition (Figure 1B). This hypothesis was tested with a mixed ANOVA with one between-subjects factor (T1-pair Predictable or Unpredictable) and two within-subject factors: Lag (2 levels: 1, 3) and T2-pair location (2 levels: in-stream, between-streams). The analysis revealed significant main effects of Lag, $F(1, 24) = 7.27$, $p = .013$, $\eta^2 = .23$, and T1-pair location, $F(1, 24) = 121.37$, $p = .001$, $\eta^2 = .84$. There were also two significant two-way interactions: T1-pair location × T2-Pair location, $F(1, 20) = 15.45$, $p = .001$, $\eta^2 = .39$, and Lag × T1-pair location, $F(1, 24) = 6.62$, $p = .017$, $\eta^2 = .22$. Finally, the Lag × T1-pair location × T2-pair location interaction was significant, $F(1, 24) = 8.11$, $p = .009$, $\eta^2 = .25$. No other effects were significant.

A salient secondary aspect of the data is also worth noting: the magnitude of Lag-1 sparing in the T1-pair Unpredictable condition is greater when the T2-pair appears in the same location as the T1-pair. Notably, this is the case regardless of whether the T1-pair appeared in-stream or between-streams, as evident in the crossover in Figures 1B and 1C: Lag-1 sparing is greater when the T2-pair appears in-stream (Figure 1B, filled circles), but greater when the T2-pair appears between-streams (Figure 1C, empty circles), $F(1, 20) = 15.45$, $p = .001$, $\eta^2 = .39$. We will address this secondary finding and its relation to the main hypothesis in the discussion to follow.

Discussion

The results indicate that both modes of attentional deployment—unitary and divided—can be observed for the same sequence of visual stimuli. Whether one mode or the other is employed in any given instance depends on whether the observer expects to deploy attention initially (in order to identify the T1-pair) to only in-stream locations or to all locations.

As outlined in the Introduction, Lag-1 sparing occurs only if T2 falls within the focus of attention, and the incidence of Lag-1 sparing therefore provides an ideal tool for probing the distribution of attention (e.g., Jefferies et al., under review; Jefferies & Di Lollo, 2009; Jefferies, Ghorashi, Kawahara & Yamada, 2006; Lunau & Olivers, 2010; Kawahara & Yamada, 2007). One might ask, however, why we do not simply compare T2-pair identification accuracy at Lag 1 in the various experimental conditions. The reason is that accuracy at Lag 1 may be influenced by more than one factor and can therefore be difficult to interpret. Consider, for example, the data illustrated in Figure 1A. Unless one takes into account the fact that T2-pair accuracy at Lag 3 is almost identical in the in-stream and between-streams conditions, the greater accuracy of Lag 1 in the in-stream condition could simply be attributable to differences in overall task difficulty between the conditions. Such differences are controlled when defining Lag-1 sparing as the difference in accuracy between Lags 1 and 3. For this reason, we assessed Lag-1 sparing to probe the distribution of attention and to determine whether focal attention was unitary or divided.[2]

This main conclusion, which concerns how the spatial distribution of attention affects Lag-1 sparing, must be placed in the context of a second factor that operates independently in the current experiment, namely, the spatial coincidence of the T1- and T2-pairs. There are many reports in the literature that the magnitude of Lag-1 sparing is greater when T1 and T2 appear in the same spatial location (e.g., Du, Abrams, & Zhang, 2011; Jefferies & Di Lollo, 2009; Juola, Botella, & Palacios, 2004; Kawahara, 2002; Olivers, 2004; Visser, Bischof, & Di Lollo, 1999). The powerful effect of this factor can be seen in this study by considering Panels B and C of Figure 1: the magnitude of Lag-1 sparing is greater when the T2-pair appears in the same location as the T1-pair, regardless of whether the targets appear in-stream (filled circles in Panel B) or between-streams (empty circles in Panel C). When the T2-pair appears in a different location from the T1-pair, Lag-1 sparing is still evident (as expected, because the T2-pair appears in an attended region), but its magnitude is reduced. To summarize, whereas the distribution of attention determines the incidence of Lag-1 sparing, the spatial coincidence of T1 and T2 determines the magnitude of Lag-1 sparing, and these two factors are both evident in the current results.

Although we interpret the current results as indicating that observer expectation determines whether focal attention is unitary or divided, several alternative explanations can be considered. First is the possibility that what appears to be a divided attentional focus is, in fact, a unitary focus shifted rapidly between the target locations. This seems unlikely in the present study for the following three reasons: First, the targets are pairs of letters that appear simultaneously at separate locations. Making a correct response depends on comparing the two letters, thus a rapid-switching

[2] Although we consider Lag-1 sparing as our main measure, it is worth noting that the absolute levels of Lag 1 data also support our hypothesis. Accuracy at Lag 1 is significantly lower in the Predictable condition (Figure 1, Panel A, empty circles) than in the Unpredictable condition (Figure 1, Panel B, empty circles), $t(10) = 1.87$, $p < .05$. Thus, absolute accuracy at Lag 1 leads to the same conclusion; the central region is unattended in the Predictable condition but attended in the Unpredictable condition.

interpretation would require that one letter be identified, a switch occur between the streams, and then a second letter be identified all within the 70-ms exposure duration. This short exposure duration (especially when combined with simultaneous, spatially separated targets) seems sufficient to preclude a rapid switching account (e.g., Cave, Bush, & Taylor, 2010; Jans, Peters, & De Weerd, 2010; Weichselgartner & Sperling, 1987). Further, given the distinct pattern of T2-pair accuracies in the T1-pair Predictable and the T1-pair Unpredictable conditions, the pattern of rapid switching must necessarily have differed between the T1-pair Predictable and the T1-pair Unpredictable conditions, and there is no clear reason why this might be the case. Finally, in a paradigm very similar to that used in the current study, Weichselgartner and Sperling (1987) showed that it takes more than 200 ms to switch focused attention from one RSVP stream of letters to another.

Another alternative interpretation can be considered. It is possible that in the T1-pair Unpredictable condition, instead of focal attention being unitary, the focus is divided, but given the expectations of the observer, the spatial extent of each focus expands to encompass the adjoining portion of the between-streams region. In this case, the area between the streams would be attended and Lag-1 sparing would occur, even though the focus of attention is divided. We consider the unitary-focus interpretation to be more plausible for two reasons. First, one reason for dividing the focus of attention might be to prevent the processing of irrelevant, distracting stimuli. Because in the current experiment the central region contains only a fixation cross, there is no need to exclude that area. Second, and perhaps more important, it has been shown that: (a) a physically visible stimulus is necessary for the focus of attention to be divided (Castiello & Umiltà, 1992; Turatto et al., 2000), and (b) that the focus of attention reflexively expands or contracts to match the physical extent of a stimulus (Castiello & Umiltà, 1990; Maringelli & Umiltà, 1998). For the divided foci to be broadened to encompass the central region, each focus would have to expand to include an empty region of space, which, given (a) and (b) above, seems implausible.

A third and final alternative interpretation to consider is that instead of the focus of attention being divided in the Predictable condition, the focus maintains its unitary form and an area of suppression is applied to the central region between the two streams, resulting in the focus of attention being shaped as an annulus or a donut (e.g., Müller & Hübner, 2002; see Jans, Peters, & de Weerd, 2010, for an in-depth discussion of the annulus interpretation). In the current study, an attentional annulus would encompass not only the two streams where the targets appear, but also the extensive regions between the streams above and below fixation. As a result, considerable attentional resources would be allocated to regions where stimuli are never presented, which would be relatively inefficient. Further, it seems likely that the mechanism required to define and maintain such an annular distribution of attention, particularly when it involves an empty region of space, might be more complex than a mechanism that maintains attention to two separate locations (see Cave, Bush, & Taylor, 2010). There is also compelling experimental evidence to speak against an annulus-shaped attentional focus in a paradigm very similar to that of the current study. Visser, Bischof, and Di Lollo (2004) employed an attentional blink paradigm in which a stream of distractors was presented at fixation while targets appeared randomly above, below, to the left or to the right of fixation. Critically, as was specified in the instructions to the observers, the targets never appeared in the central stream. Despite this, the presence of the central stream caused identification of both target letters to be substantially impaired. Had the observers been able to deploy an annulus-shaped attentional focus, no impairment (or a much smaller impairment) would have been in evidence. In sum, we consider an annulus to be relatively unlikely in the current experiment, although future research would be required to definitively eliminate the possibility.

In conclusion, the flexible deployment of attention across space and time is critical for the efficient extraction of information from the world. The research reported here confirms that the focus of attention can be deployed flexibly in either a unitary or a divided mode, and specifies one set of conditions under which this flexible division takes place. In particular, the results show that the expectations of the observer regarding how spatial attention will be deployed in a given instance can lead to diametrically different outcomes for physically identical second-target displays. This means that a simple change in the goals of the observer can nudge the mode of attentional deployment within a task from unitary to divided or vice versa.

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