The role of attention in temporal integration

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Abstract. When two visual patterns are presented in rapid succession, their contours may be combined into a single unified percept. This *temporal integration* is known to be influenced by such low-level visual factors as stimulus intensity, contour proximity, and stimulus duration. In this study we asked whether temporal integration is modulated by an attentional-blink procedure. The results from a localisation task in experiment 1 and a detection task in experiment 2 pointed to two separate effects. First, greater attentional availability increased the accuracy of spatial localisation. Second, it increased the duration over which successive stimuli could be integrated. These results imply that theories of visible persistence and visual masking must account for attentional influences in addition to lower-level effects. They also have practical implications for use of the temporal-integration task in the assessment of group and individual differences.

1 Introduction

It has long been known that an object remains visible for a short time after the object itself has disappeared from view. This phenomenon, known as *visible persistence*, can be demonstrated informally by waving a finger rapidly back-and-forth. What appears is not a single, clearly defined finger in motion, as might be expected, but a blurred image of the finger that appears to be in several places at once. This surprising outcome suggests that a mental representation of a briefly presented image persists for a period after the stimulus has been terminated. As a result, successive images of the finger are fused into a composite image, corresponding to where the finger is at any moment, and where it was moments ago.

Visible persistence has been studied systematically with a variety of *temporal-integration* tasks. One example is the missing-dot localisation task (Hogben and Di Lollo 1974). Here, the stimulus consists of 24 dots arranged in a 5×5 matrix with a single dot removed. This matrix is presented in two frames of 12 dots, separated by a variable interstimulus interval (ISI) during which the screen is blank. Observers are required to report the location of the missing dot. Because of the large number of dots, it is assumed that accurate localisation can only be achieved by integration of the two frames into a single percept. It follows from this that the duration of visible persistence of the first frame of dots is indicated by the maximum ISI at which localisation is still possible.

Using this and similar methods, studies have demonstrated that temporal integration is influenced by such factors as exposure duration (eg Di Lollo 1980), stimulus luminance (eg Di Lollo et al 1988; Long and Beaton 1982), and interdot spacing (eg Di Lollo and Hogben 1987). Such findings, in turn, have motivated theoretical accounts of temporal integration that are couched entirely in terms of low-level visual mechanisms. For example, Coltheart (1980) suggested that temporal integration arises from continued activity in the *sustained* visual channel after stimulus offset. The duration of this activity, however, is modulated by activity generated in the *transient* visual channel by the onset of new stimuli. Other accounts of persistence have even attributed it entirely to continued activation at the level of the photoreceptors. For example, Sakitt and colleagues (Long and Beaton 1982; Sakitt 1976; Sakitt and Long 1978) argued that temporal integration arises from inherent limitations in the temporal resolution of retinal cells.

Although the evidence in favour of low-level explanations is both copious and compelling, very little research has been carried out to establish whether high-level processes, such as visual attention, might also modulate temporal integration. This possibility is suggested by a growing number of studies showing that other putatively low-level visual phenomena, such as contrast sensitivity (Carrasco et al 2000), pop-out detection (Joseph et al 1997), and metacontrast masking (Enns and Di Lollo 1997) are influenced by attention. Consider metacontrast masking, which refers to a reduction in the visibility of an initial target by the presentation of a second masking stimulus that is temporally trailing and spatially adjacent. Like temporal integration, it is influenced by adapting luminance conditions (Petry et al 1979), stimulus luminance (Alpern 1953), and background luminance (Purcell et al 1974). This has fuelled theories which attribute metacontrast to the interaction between transient and sustained visual channels (Breitmeyer 1984). However, numerous studies have now demonstrated that metacontrast is also heavily influenced by visual attention, implying at a minimum that any explanation based solely on low-level mechanisms is incomplete (Averbach and Coriell 1961; Di Lollo et al 2000; Enns and Di Lollo 1997; Ramachandran and Cobb 1995; Shelley-Tremblay and Mack 1999; Spencer and Shuntich 1970).

Suggestive evidence for a possible link between attention and temporal integration comes from studies of the effect of focused attention on the perceived duration of a stimulus. Enns et al (1999), and Mattes and Ulrich (1998) compared observer's duration judgments for test flashes appearing both at cued and at uncued spatial locations. Flashes in cued locations were judged to be as much as 18 ms longer than those in uncued locations; an overestimation of 25% for a 70 ms flash. This suggests that attending to a flash significantly prolonged its perceived duration. On the assumption that an increase in the perceived duration of a stimulus would also prolong the period so that it could be integrated with a subsequent stimulus, these results suggest that attention may enhance temporal integration.

In light of this evidence, the goal of the present study was to determine whether temporal integration, like contrast sensitivity, pop-out detection, metacontrast, and perceived stimulus duration, is modulated by the availability of attentional resources. To this end, we varied the availability of attention for performing the missing-dot task (Hogben and Di Lollo 1974), using an attentional-blink procedure (Joseph et al 1997). In the attentional blink, two targets are presented, separated by a temporal lag commonly ranging from 100 to 700 ms. Under these circumstances, identification of the first target is nearly perfect. However, identification of the second target varies as a function of lag, with accuracy being poorest at shorter lags and gradually improving as lag increases (eg Raymond et al 1992; Shapiro et al 1994).

As noted by Shapiro et al (1997), all current models of the attentional blink ascribe improvement in second-target identification across lags to the availability of attentional resources (eg Chun and Potter 1995; Giesbrecht and Di Lollo 1998; Jolicoeur 1998; Shapiro et al 1994). For example, in the two-stage model of Chun and Potter (1995), processing of the first target is more likely to be completed by the time the second target arrives. This increases the probability that attentional resources will be available for the second target and improves the accuracy of its identification. Whatever the exact mechanisms, the relevant point for the present work is that there is universal agreement that processing of the first target reduces attentional availability for the second target.

Our choice of the attentional-blink procedure over other attentional manipulations such as spatial cueing was motivated by the nature of our stimuli. Cueing is most effective when attention can be directed towards a clearly demarcated spatial location. However, in the present experiments, the dot matrix was composed of a number of discrete dots spread across a relatively large area of space. Under these circumstances, it was possible that spatial cues might not direct attention to the matrix as a whole,

but instead towards only a subset of dots. Presenting the matrix at fixation, and varying availability of attentional resources by using the attentional-blink procedure, obviated such complications.

In the present study, we displayed the dot-matrix sequence as the second of two targets, separated from the first target by a variable temporal lag. An influence of attention would be indicated by an improvement in performance as lag was increased. An important additional question concerned the locus of this effect. This question arises because successful performance cannot be attributed unambiguously to successful integration per se. Other factors, such as the visibility of the matrix elements in each frame, must also be taken into account. In the present study, we considered two possibilities. One is that attentional availability modulates successful temporal integration directly through an increase in the visible persistence of individual display frames (Enns et al 1999). This should serve directly to improve accuracy in the missing-dot task. A second possibility is that greater attentional availability improves the accuracy with which the dot patterns are seen, both in individual frames and in the integrated frames. On this option, the accuracy of pattern perception is improved by attentional availability because the dot patterns are perceived with higher spatial resolution (Enns and Di Lollo 1997) or because the dots are more accurately localised (Ashby et al 1996; Treisman and Gelade 1980).

In order to distinguish these possibilities, we compared accuracy in missing-dot tasks when the frames were presented simultaneously (ISI = 0 ms) with that when the frames were separated by a positive ISI. Importantly, when the frames are simultaneous, no integration is required to localise or detect a missing dot. Any differences in the effects of attention for simultaneous and successive frame conditions can therefore be used to separate the effects of attention on pattern perception from those of temporal integration. To illustrate this point, two possible patterns of accuracy across ISI should be considered. In one, accuracy is improved by greater attentional availability at all ISIs, including critically the 0 ms ISI condition. Because this attentional influence is observed even when temporal integration is not required in the task, it points to an influence of attention on perception of the dot patterns over and above any possible influence on temporal integration. In a second possible outcome, accuracy is impaired at positive ISIs, but not at the 0 ms ISI. This outcome suggests that focusing attention improves the efficiency of temporal integration without a concomitant improvement in pattern perception.

In the following experiments, we applied this analysis to both a missing-dot localisation task (experiment 1) and a missing-dot detection task (experiment 2). We reasoned that the localisation task would depend more heavily than the detection task on accurate perception of the spatial details of the dot patterns. As such, any influence of attention on pattern perception should be more readily observed in the first than in the second experiment.

2 Experiment 1: Missing-dot localisation

Observers were presented with two targets. The first target was a letter that had to be classified as either a vowel or a consonant. The second target was a 5×5 dot matrix with two missing dots. One missing dot was always at the centre of the matrix where the letter was presented. A second missing dot occurred at a random location that was to be reported by observers at the end of each trial. Temporal integration was assessed by separating the two frames of the missing-dot task by an ISI of 0, 20, 40, 60, or 80 ms. Attentional availability was modulated over time by inserting a variable temporal lag between the first and second targets of either 100, 300, or 700 ms.

The influence of attention was further assessed by comparing a group of observers that ignored the letter and only performed the missing-dot task (single task), with a

group that performed both the letter-classification and missing-dot tasks (dual task). Improvements in accuracy over lag were not generally expected for the single-task group, since they could devote all processing resources to the missing-dot task. Any residual lag effects in this group would therefore be attributed to involuntary processing of the central letter (Chun 1997; Potter et al 1998) and/or to the sudden onset of the letter and digit mask in the central location (Yantis 1993). Both of these effects subside rapidly over approximately 100 ms from stimulus onset.

2.1 Method

2.1.1 *Participants.* Twenty undergraduate students from the University of British Columbia participated for class credit. Subjects were divided equally between the single-task and dual-task groups based on order of arrival to the laboratory. All had normal or corrected-to-normal vision based on self-report.

2.1.2 *Apparatus and stimuli.* All stimuli had a luminance of 100 cd m^{-2}, as measured by a Minolta LS-100 luminance meter, and were displayed on a Tektronix 608 oscilloscope, equipped with fast P15 phosphor. The background and surrounding visual field were dark, except for dim illumination of the keyboard.

The central letter was either a vowel (A, E, I, O, U) or a consonant (V, T, L, P, C), chosen randomly, followed by a single digit serving as a backward mask that was chosen randomly from the set $1-8$. At a viewing distance of 57 cm, set by a headrest, the letter and the trailing digit mask each subtended approximately 1 deg. The second target was a 5×5 square matrix of dots, which subtended 3 deg. One dot in the middle of the matrix was never displayed to avoid spatial overlap between the letter and the dots. A second dot was removed at random from one of the 24 remaining locations. The remaining 23 dots were randomly displayed, with 11 dots in the first and 12 dots in the second frame, or vice versa.

2.1.3 *Procedure.* Each trial began with a small fixation cross in the centre of the screen. Observers initiated the following sequence by pressing the space bar. The screen was blank for 200 ms, followed by the central letter for 40 ms, a blank screen of 60 ms, and then the central digit mask for 40 ms. The first frame of the dot matrix, also centred in the screen, followed the letter at either 100 ms, 300 ms, or 700 ms (henceforth, lags 1, 3, and 7). The first and second frames of the matrix were each displayed for 1 ms and were separated by a variable ISI of either 0, 20, 40, 60, or 80 ms, during which the screen was blank.

In the dual-task condition, observers first indicated whether the letter was a vowel or a consonant by pressing one of two labelled keys. They then indicated a location in the matrix where a dot was missing. This was accomplished by pressing two buttons on a response box: the first to indicate the column, and the second the row. In the single-task condition, observers were required only to specify the column and row where a dot was missing. Observers were informed at the outset that a dot would never appear in the central location in the matrix, and that they should examine the other locations for a missing dot. After observers completed their responses, the fixation cross reappeared to indicate the beginning of the next trial.

All observers completed a total of 320 trials: 20 practice trials and 300 experimental trials. During the first 10 practice trials, observers located the missing dot in matrices that were presented at variable lags, but both frames of dots were presented simultaneously (ISI = 0 ms). During the next 10 practice trials, matrices were presented at variable lags and the two frames of the matrix were separated by a variable ISI. The 300 experimental trials were divided equally between conditions, such that there were 20 trials for each of the four ISIs at each of the three lags. The order of these trials was randomly determined for each observer.

2.2 *Results and discussion*

Accuracy in the missing-dot task was based exclusively on trials in which the central letter had been classified correctly as a vowel or a consonant. This is common practice in studies of the attentional blink, because only when the first target is classified correctly there is a reasonable assurance that it was attended. Figure 1 shows correct missing-dot localisation as a function of task (single versus dual) and the ISI between the frames in the dot matrix. Figures 1a, 1b, and 1c illustrate this relationship for lags 1, 3, and 7, respectively.
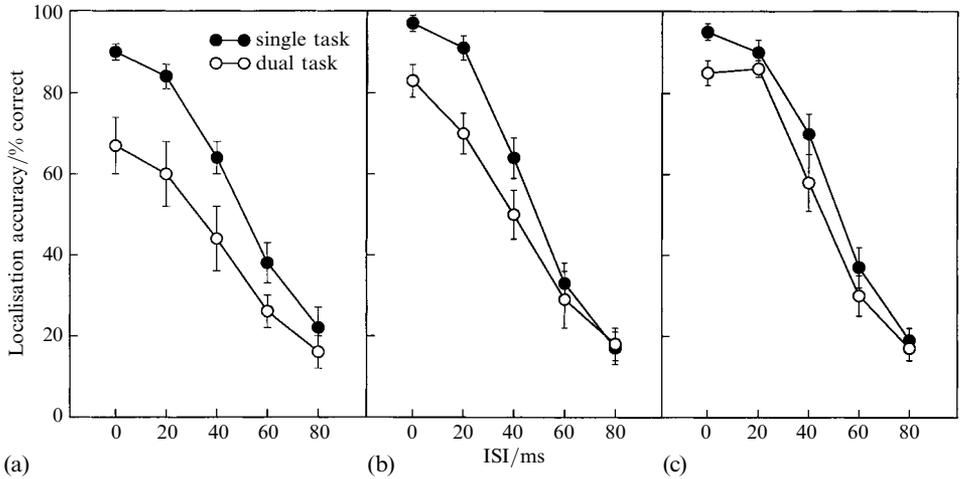

Figure 1. Mean percentage accuracy in missing-dot localisation as a function of interstimulus interval (ISI) and task, contingent on the letter target being correctly classified. Error bars represent 1 standard error of the mean. (a), (b), and (c) show performance at lags 1, 3, and 7, respectively.

Inspection of figure 1 indicated three notable results. First, accuracy declined as ISI increased, reflecting the expected breakdown of temporal integration over increasing time intervals between display frames in the missing-dot task. Second, there was a clear benefit in accuracy for the single task relative to the dual task. Third, the size of this benefit declined as lag increased. This interaction between task and lag indicates an influence on attention on missing-dot localisation accuracy.

These observations were confirmed by an analysis of variance (ANOVA) for Task (single, dual), ISI (0, 20, 40, 60, 80 ms), and Lag (1, 3, 7). It revealed significant main effects of Task ($F_{1, 18} = 8.57$, MSe $= 0.112$, $p < 0.01$), ISI ($F_{4, 72} = 168.27$, MSe $= 0.031$, $p < 0.001$), and Lag ($F_{2, 36} = 10.29$, MSe $= 0.014$, $p < 0.01$); and significant interactions of Task $\times$ Lag ($F_{2, 36} = 4.60$, MSe $= 0.031$, $p < 0.001$), and Lag $\times$ ISI ($F_{8, 144} = 3.63$, MSe $= 0.0009$, $p < 0.002$). The Task $\times$ ISI interaction was marginally significant ($F_{4, 144} = 2.06$, MSe $= 0.008$, $p < 0.10$), but the interaction of Task $\times$ ISI $\times$ Lag was not ($F_{8, 144} = 1.08$, MSe $= 0.008$, $p > 0.20$).

To examine the significant Task $\times$ Lag interaction more closely, separate analyses were conducted at each lag. For both lags 1 and 3 (figures 1a and 1b) there were significant differences between groups ($F_{1, 18} = 11.24$, MSe $= 0.063$, $p < 0.005$; and $F_{1, 18} = 6.40$, MSe $= 0.041$, $p < 0.001$, respectively). However, for lag 7 the group difference was no longer significant ($F_{1, 18} = 3.24$, MSe $= 0.036$, $p > 0.05$).

These results point clearly to an influence of attention on accuracy; what is less obvious is the origin of this effect. As noted in section 1, this question can be addressed by comparing ISI $= 0$ ms, where integration is not required, with accuracy at positive ISIs where integration is required. It is clear in these data that the attentional effects are large even when no temporal integration is required (ISI $= 0$ ms).

This result is entirely consistent with those obtained in previous attentional-blink experiments (eg Chun and Potter 1995; Raymond et al 1992). These data therefore support the hypothesis that missing-dot accuracy is improved in the single-task and long-lag conditions because attentional availability improves pattern perception. Such an improvement could be attributable to at least two sources. One is an increase in the spatial resolution of the dot matrix (eg Tsal et al 1995). On this account, increased attentional availability allowed the individual dots to be perceived more clearly, thereby improving localisation of the missing dot. A second source of improvement could arise from an increased ability to accurately localise the dots (eg Ashby et al 1996; Treisman and Gelade 1980). More accurate localisation of the dots would allow the missing dot to be more easily localised as well. It remains for future research to distinguish between these possibilities.

Before attributing the attentional effects in the present experiment entirely to benefits in pattern perception, another possibility must be considered. It is possible that the results of the present experiment reflect the combined influence of attention on pattern perception and temporal integration. On this option, although single-task accuracy at ISI = 0 ms can be explained entirely on the basis of enhanced pattern perception over dual-task accuracy, performance at positive ISIs may reflect an additional benefit due to an attentional influence on temporal integration. Such an account would increase in plausibility if accuracy differences between task were larger at some positive ISIs than they are at 0 ms. Indeed, there are hints that this is the case for at least one lag (lag 3, figure 1b).

In order to investigate this possibility more systematically, we modified the missing-dot task in experiment 2 to make it less dependent on accurate pattern perception. To do so we used a missing-dot detection task in which observers indicated whether or not a missing dot was present in the array, regardless of where the missing dot was located. A number of previous experiments are consistent with our assumption that a detection task is less dependent on the availability of attentional resources than localisation (eg Bennett and Jaye 1995; Di Lollo et al, in press; Sagi and Julesz 1985). For example, Bennett and Jaye (1995) compared discrimination and localisation accuracy for a target letter presented amongst a variable number of distractor letters. They found that target localisation thresholds were significantly more impaired by an increase in the number of distractor letters than were discrimination thresholds, suggesting that localisation requires more attentional resources than discrimination.

We also noted a secondary and somewhat unexpected finding in passing, namely that accuracy in the single-task condition at ISI = 0 ms was slightly depressed in lag 1 relative to lags 3 and 7 ($F_{2, 18} = 6.54$, MSe $= 0.015$, $p < 0.01$). Such a lag-dependent effect is surprising, given that observers were instructed to ignore the letter in this condition. One possible explanation is that, despite the instructions to ignore the central letter, observers were unable to do so completely (Chun 1997; Potter et al 1998). A second and perhaps simpler explanation is that the digit mask following the letter was presented at exactly the same time as the onset of the first frame of dots. Involuntary attentional capture by the sudden appearance of a new item is both a well known effect and one that also diminishes rapidly with time (Yantis 1993).

3 Experiment 2: Missing-dot detection

If the missing-dot detection task depends less heavily on pattern perception than the localisation task, accuracy differences between single and dual tasks should be minimised when the dots are all presented in the same display frame (ISI = 0 ms). In addition to this change in task, two other changes were made to the design of the experiment. First, the size of the dot matrix was increased to 7×7 because pilot data indicated that missing-dot detection in the smaller 5×5 matrix yielded no differences between single-task and dual-task conditions at any lag or ISI. The size of the matrix

was therefore increased on the assumption that detection in the smaller matrix was not sufficiently difficult for an attentional influence to be evident. Second, each observer participated in both the single-task and dual-task conditions, in an attempt to increase the statistical power of the experiment. On each trial, observers were simply asked to report whether the matrix contained a missing dot or not.

3.1 Method
3.1.1 *Participants.* Twenty-six undergraduate students from the University of British Columbia participated for class credit. All had normal or corrected-to-normal vision based on self-report, and none had participated in the previous experiment.

3.1.2 *Apparatus and stimuli.* The apparatus and stimuli were identical to those in experiment 1, except for the 7×7 dot matrix, which subtended 4.2 deg.

3.1.3 *Procedure.* With the exception of the task performed by observers, the procedures were identical to those in experiment 1. To accommodate the detection task, the matrix was presented with a missing dot on only one half of the trials. On each trial, observers indicated whether they had seen a missing dot or not by pressing one of two keys. Observers completed 300 experimental trials in both the single-task and dual-task conditions in a single session of approximately 1 h, in counterbalanced order.

3.2 Results and discussion
Figures 2a, 2b, and 2c show correct missing-dot detection as a function of task (single versus dual) and the ISI between the frames in the dot matrix for lags 1, 3, and 7, respectively.
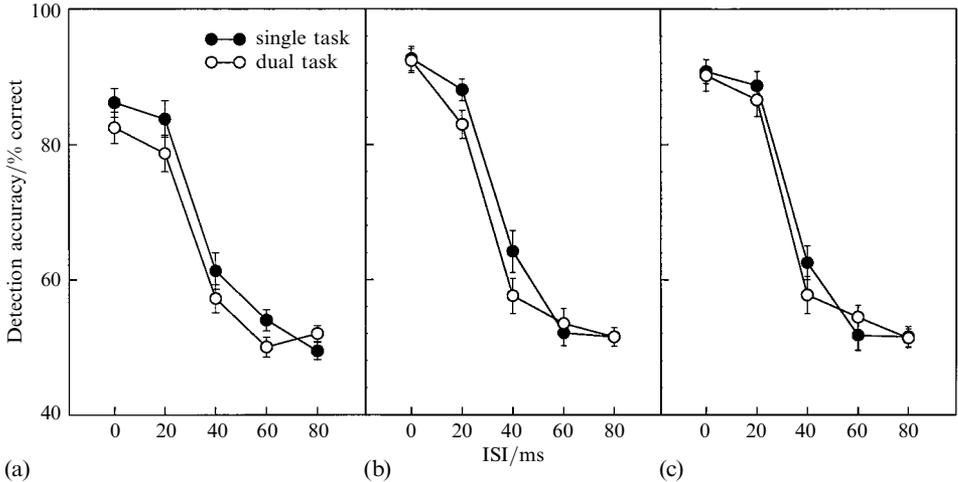

Figure 2. Mean percentage accuracy in missing-dot detection as a function of interstimulus interval (ISI) and task, contingent on the letter target being correctly classified. Trials on which errors were made on the first target were excluded. Error bars represent 1 standard error of the mean. (a), (b), and (c) show performance at lags 1, 3, and 7, respectively.

Inspection of these results indicated that detection accuracy decreased with ISI, that accuracy was generally higher in the single-task than in the dual-task condition, and that the size of this task difference varied with ISI. These observations were confirmed by ANOVA, which revealed significant main effects of Task ($F_{1,25} = 8.26$, MSe $= 0.010$, $p < 0.01$), ISI ($F_{4,75} = 209.43$, MSe $= 0.024$, $p < 0.001$), and Lag ($F_{2,50} = 9.67$, MSe $= 0.009$, $p < 0.01$); and significant interactions of Task $\times$ ISI ($F_{4,75} = 5.19$, MSe $= 0.005$, $p < 0.01$), and Lag $\times$ ISI ($F_{8,150} = 2.60$, MSe $= 0.007$, $p < 0.01$). No other effects were significant (all $ps > 0.20$).

As in experiment 1, more detailed analyses examined the effects of Task and ISI at each lag. For lag 1 (figure 2a), there was a significant main effect of Task ($F_{1,25} = 9.51$, $MSe = 0.054$, $p < 0.01$), and a Task $\times$ ISI interaction ($F_{4,100} = 2.56$, $MSe = 0.012$, $p < 0.05$). Pairwise comparisons of task differences at each ISI indicated significance at ISIs $= 20$ ms and 40 ms only ($p < 0.05$). For lag 3 (figure 2b) there were also a significant main effect of Task ($F_{1,25} = 5.92$, $MSe = 0.05$, $p < 0.03$), and a Task $\times$ ISI interaction ($F_{4,100} = 2.48$, $MSe = 0.006$, $p < 0.05$). Here pairwise comparisons of task differences at each ISI indicated significance at ISIs $= 20$ ms and 40 ms but not at any other ISIs ($p < 0.05$). Finally, for lag 7 (figure 2c), there was neither the main effect of Task ($F_{1,25} = 0.84$, $MSe = 0.008$, $p > 0.05$), nor a Task $\times$ ISI interaction ($F_{4,100} = 1.76$, $MSe = 0.006$, $p > 0.10$). Only one pairwise comparison of task differences was significant (ISI $= 40$ ms, $p < 0.05$).

These results therefore again indicated an effect of attention on temporal integration: missing-dot detection accuracy depended on both task condition and lag. These results, however, point more clearly than those in experiment 1 to an attentional effect that was specific to temporal integration. The strongest evidence came from the pattern of task differences over ISI. In the present experiment, these tended to be largest for positive ISIs, rather than for ISI $= 0$ ms, as they were in experiment 1. This suggests that the detection of a single missing dot in a single temporal frame could be accomplished quite well under conditions of either full or divided attention. However, once the dot matrix was presented in two successive frames, detection accuracy was significantly greater in the single-task than in the dual-task condition.

As in experiment 1, we noted that accuracy in the single-task condition at ISI $= 0$ ms was depressed in lag 1 relative to lags 3 and 7 ($F_{2,50} = 6.95$, $MSe = 0.005$, $p < 0.01$). We again attributed this effect to either an involuntary perceptual intrusion of the letter (Potter et al 1998), or the digit mask (Yantis 1993), and note that in this experiment the effect seemed to extend to an ISI of 20 ms. This is an effect that, although not of central interest in the present study, should be examined in greater detail in future studies.

4 General discussion

In the present study we asked whether the integration of visual information across time is influenced by attention. To study temporal integration, we used two variations of the missing-dot task in which a square matrix of dots is presented in two sequential frames, separated by a variable interval (Hogben and Di Lollo 1974). In experiment 1, observers attempted to localise a missing dot, while in experiment 2, they tried to detect whether a dot was missing or not. Attentional availability for these tasks was manipulated with an attentional-blink procedure.

The results pointed to the influence of attention on both missing-dot tasks. In experiment 1, a benefit in localisation accuracy was found when more attentional resources were available, both when no temporal integration was required (ISI $= 0$ ms) and when temporal integration was required (positive ISIs). In experiment 2, these effects were larger for the positive ISI conditions than when ISI was zero. Taken together, these results point to two sources of attentional influence in the temporal-integration task.

The first influence concerns the benefits of attentional availability on pattern perception. This benefit is therefore akin to that found in other studies in which focused attention is seen to benefit low-level aspects of perception such as contrast sensitivity (Carrasco et al 2000), pop-out detection (Joseph et al 1997), and metacontrast masking (Enns and Di Lollo 1997). The second benefit, however, is unique to temporal integration in that it benefits accuracy specifically when successive frames of information must be combined. Taken together with the previous work on the influence

of attention on perceived duration of a brief stimulus (Enns et al 1999; Mattes and Ulrich 1998), these present results imply that, when attended, brief stimuli are visible for a longer period, and that this added duration of the mental representation can be combined with succeeding stimuli.

4.1 Implications for theories of temporal integration and masking

One implication of these findings is that, like theories of metacontrast masking, theories of temporal integration must be revised to account for the influence of higher-order processes such as visual attention. As noted in section 1, current accounts of temporal integration are couched entirely in terms of low-level mechanisms. The present findings therefore show that they are incomplete: new ideas are required that allow for low-level and high-level mechanisms to operate interactively.

One framework for such a theory is the reentrant pathway model proposed by Di Lollo et al (in press, a) to explain a variety of visual masking effects. In brief, perception is said to arise from the establishment of an iterative processing loop between higher brain centres involved in object perception and lower brain regions involved in sensory registration. In the context of temporal integration, such interactivity would serve to magnify and prolong the sensory signals associated with the object of attention, because there is a high level of agreement between the expectations generated by higher brain centres and the incoming sensory data. At the same time, one of the limitations of the brain is that only a very small set of these iterative loops can bring their products to consciousness at a time. Therefore, objects that are outside the focus of attention are vulnerable to being replaced by the ongoing temporal stream of visual information (Brehaut et al 1999; Enns and Di Lollo 1997; Giesbrecht and Di Lollo 1998). Such replacement has been termed object substitution masking (Di Lollo et al 2000; Enns and Di Lollo 1997).

For the present experiments, we can only speculate whether the increased period of temporal integration for attended dot matrices reflects the *benefit* of prolonging the signal of the attended first frame in the dot matrix, or whether it reflects the *cost* of object substitution by the second frame of dots when the dot matrix is unattended. In future experiments, it may be possible to distinguish between these possibilities by varying attentional factors at the same time as varying low-level factors that are likely to influence the perceived duration of the first frame. Previous research suggests the relevant low-level factors which act to decrease the persistence of the first frame are increases in frame duration (Di Lollo 1980) and adapting luminance (Di Lollo et al 1988). In contrast, decreases in interdot spacing seem to work against temporal-integration accuracy by increasing the likelihood of perceptual substitution of the first frame by the second frame (Di Lollo et al 2000; Di Lollo and Hogben 1987). Therefore, studies of the patterns of interaction between these factors and attentional availability should help to clarify the relative roles played by signal prolongation versus object substitution in the present pattern of results.

A second implication of the present findings applies to theories of visual masking. As noted in section 1, there are a growing number of reports that masking by object substitution, as exemplified in metacontrast and backward pattern masking, is heavily influenced by visual attention (Brehaut et al 1999; Chun and Potter 1995; Di Lollo et al 2000; Enns and Di Lollo 1997; Giesbrecht and Di Lollo 1998). What has not been addressed as thoroughly, however, are potential effects of visual attention on masking by temporal integration or camouflage (Bachmann and Allik 1976; Scheerer 1973; Spencer and Shuntich 1970). The present finding suggests that such effects may indeed exist, although they may be smaller in size than is the case for masking by substitution. Some corroborating evidence for this suggestion may be found in attentional-blink studies by Giesbrecht and Di Lollo (1998) and Brehaut et al (1999). Although, taken

singly, none of these studies revealed a statistically significant relationship between attention and integration masking, there is a general trend across experiments that points to reduced integration masking for attended targets. Future work should follow-up on this work in order to confirm these suggestive trends. In addition, it may be fruitful to use other paradigms to examine the effect of attention. For example, strength of masking could be examined as a function of set size in a visual-search paradigm. By combining results from the attentional-blink and visual-search paradigms, stronger converging evidence may be obtained for a link between attention and integration masking.

The present findings may also have implications for the interpretation of individual or group differences in the temporal-integration task. A number of previous studies have examined temporal integration as a function of observer age (Di Lollo et al 1983a), reading ability (Di Lollo et al 1983b), or both variables (Arnett and Di Lollo 1979). The present results suggest that to the extent that observers in these groups differ in the ability to allocate attention efficiently, the temporal-integration task may not reflect purely on the duration of visible persistence. Instead, temporal-integration accuracy may also reflect observer differences in pattern perception and attentional deployment. Future studies of individual or group differences in temporal integration would therefore be well advised to include appropriate control conditions (eg accuracy when ISI = 0 ms) and to index attention independently of performance on the temporal-integration task.

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