Attention, Perception, & Psychophysics (2022) 84:341–346
https://doi.org/10.3758/s13414-021-02431-w

SHORT REPORT

Metacontrast masking reduces the estimated duration of visible persistence

Thomas M. Spalek[1] · **Vincent Di Lollo**[1]

Accepted: 21 December 2021 / Published online: 14 January 2022

Abstract

A brief visual display can give rise to a sensation that outlasts the duration of the physical stimulus. The duration of this visible persistence has been estimated with paradigms that require the temporal integration of two brief sequential displays (frames) separated by a blank temporal gap. Temporal integration is said to occur when the visible persistence generated by the first frame is sufficiently long to bridge the inter-frame temporal gap. The longest gap at which integration still occurs is taken as an estimate of the duration of visible persistence. In the present work, we show that the duration of visible persistence has been underestimated in at least some of the experiments involving the temporal integration of successive displays. This is because the trailing frame can act as a metacontrast mask that foreshortens the visibility of the leading frame. Specifically, we show that operations that reduce the strength of metacontrast masking yield longer estimates of visible persistence. The relationship between metacontrast masking and visible persistence had been mentioned in some individual studies, but a comprehensive examination of that relationship is currently unavailable. Finally, we show that estimates based on single displays (e.g., the Sperling paradigm) also fail to provide untainted estimates because, in single displays, visible persistence is confounded with informational persistence.

Keywords Temporal integration · Temporal persistence · Metacontrast masking · Visual perception

A brief visual display can give rise to a sensation that outlasts the duration of the physical stimulus. Coltheart (1980) termed the added period of visibility *visible persistence*. Visible persistence has been studied with a paradigm that entails the synthesis of a pattern whose parts are displayed in rapid sequence. The basic display consists of a 5 x 5 square matrix of dots. One of the 25 dots, chosen randomly on each trial, is not displayed. The observer's task is to identify the matrix location of the missing dot.

To study visible persistence, the remaining 24 dots are displayed in two successive frames of 12 dots each, separated by a variable inter-stimulus interval (ISI). At short ISIs, the two frames are perceptually integrated and are seen as a complete 5 x 5 matrix with one missing element whose location is easily identified. Perceptual integration of the entire matrix allows the inference that the duration of the visible persistence of the first frame is sufficient to bridge the temporal gap between the frames. At longer ISIs integration fails and the display is seen as a sequence of two sets of 12 dots each. The duration of visible persistence is estimated by the longest lSI at which integration can still be performed.

Empirical studies have revealed that the duration of visible persistence is comparable in both cerebral hemispheres (Di Lollo, 1981) and varies *inversely* with three factors: (a) duration of the display (Di Lollo, 1980; Efron, 1970), (b) spatial proximity of the stimuli (Di Lollo & Hogben, 1985; Farrell, 1984), and (c) stimulus intensity (Allport, 1968; Castet et al., 1993). These are known as the *inverse duration effect*, *inverse proximity effect*, and *inverse intensity effect*, respectively.

Early theories likened visible persistence to the contents of a sensory store that begins to decay when the external stimulus is turned off (Atkinson & Atkinson & Shiffrin, 1968; Neisser, 1967; Sakitt, 1976). This storage metaphor was abandoned after the discovery of the inverse duration effect: it would be a strange store indeed that is full after a brief charge but almost empty after a long charge.

An alternative account, proposed by Di Lollo (1980), assumes that the duration of visible persistence corresponds

✉ Thomas M. Spalek
tspalek@sfu.ca

1 Department of Psychology, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6, Canada

to the duration of an early phase of processing, estimated at about 100 ms. On this hypothesis, visible persistence is time-locked to the onset – not to the termination – of the inducing stimulus. As a consequence, brief stimuli (< about 100 ms) produce long persistence but long stimuli produce no persistence at all. Temporal integration can occur only when the trailing frame of the matrix occurs during the early processing phase of the leading frame. Thus, temporal integration of successive stimuli is based not on ISI but on stimulus-onset asynchrony (SOA). Building on these ideas, Dixon and Di Lollo (1994) proposed that the goodness of temporal integration of two sequential displays is determined by the correlation in time between the visual responses to the leading and trailing displays. Temporal integration of successive displays has also been interpreted in term of the Perceptual Moment hypothesis (Stroud, 1955; White, 1963) in which integration is said to occur when the two displays fall within the same temporal moment of 100-150 ms duration.

Not considered in any of these theories is the possibility that the temporal limit of perceptual integration is set not by the duration of visible persistence but by metacontrast masking. Metacontrast masking occurs when a temporally trailing masking stimulus closely surrounds the contours of a leading target stimulus without touching them. For example, the target could be an annulus with a small gap whose orientation is to be reported, and the mask could be a slightly larger ring closely surrounding the target ring without touching it. The mask need not surround the target entirely. Masking also occurs if the target is flanked by the mask on one or both sides (e.g., Kahneman, 1967).

Metacontrast masking can interfere with temporal integration in the dot-matrix task by interrupting the processing of the leading frame. Specifically, the onset of the dots in the trailing frame can act as a metacontrast mask for the neighbouring dots in the leading frame. Integration fails because the temporal overlap between the internal representations of the two sets of dots is reduced or absent.

The possibility of a relationship between metacontrast masking and the estimated duration of visible persistence has been raised in some individual experiments (e.g., Groner et al., 1990). But a comprehensive overview of the evidence for or against that relationship is not available in the literature. In the present work we address that deficit by examining the relevant evidence pertaining to the relationship between visible persistence and metacontrast masking.

The Inverse Proximity Effect

Accounts of the inverse-proximity effect in the matrix task have been couched in terms of visible persistence whose duration is said to diminish progressively as the spatial proximity of the dots is increased (Di Lollo & Hogben, 1987; Farrell, 1984). Of special interest in the present work is the mechanism underlying the relationship between spatial proximity and visible persistence. This is because there is no obvious reason why the duration of visible persistence, as such, should be foreshortened by increasing the spatial proximity of neighbouring dots.

A word of clarification is required regarding the use of the matrix task to study visible persistence. What is measured *directly* in the matrix task is not visible persistence *per se* but temporal integration. The duration of visible persistence is *inferred* from the longest inter-frame interval at which temporal integration still occurs. The question then becomes: What are the factors that mediate the relationship between inter-dot proximity and goodness of temporal integration? One possible such factor is metacontrast masking.

The strength of metacontrast masking has been found to increase markedly as the target-mask spatial proximity is increased (Alpern, 1953; Breitmeyer et al., 1974; Dixon & Hammond, 1972; Hogben & Di Lollo, 1985). The increased strength of masking with increasing proximity has been attributed to a corresponding increment in the strength of lateral inhibition. Given that lateral inhibition is much reduced at inter-stimulus separations beyond about .5°, and is virtually absent beyond 1° (Growney et al., 1977), increments in spatial separation beyond about 1° permit the target to escape the mask-generated inhibition thus enhancing temporal integration.

Based on these considerations, the critical factor in the inverse-proximity effect is not a reduction in the duration of visible persistence, as such, but stronger masking of the leading frame by the trailing frame. As noted above, the concept of visible persistence is inferred from these contingencies and, as such, is not strictly necessary to account for the relationship between spatial proximity and temporal integration.

This is not to say that visible persistence does not exist, witness the phenomenological appearance of a burning ember at the end of a stick spun through the air that is seen as an arc of light whose length varies with velocity. Indeed, but for metacontrast masking, visible persistence may well mediate perceptual integration. But the matrix task cannot be regarded as providing an untainted estimate of the duration of visible persistence, at least with inter-dot separations of less than 1°.

The Inverse Duration Effect

Temporal integration in the matrix task is progressively impaired as the duration of the leading frame is increased. This inverse-duration effect has been attributed to a reduction in the duration of visible persistence as the duration of the leading frame is increased (Di Lollo, 1980; Duysens et al., 1985). On this account, visible persistence is generated by the burst of early processing activity time-locked to stimulus onset and is said to be available for the duration of the early processing phase – estimated at about 100 ms – regardless of whether the physical stimulus is present on the screen. Temporal integration is said to occur when the visible persistence triggered by the leading stimulus overlaps in time with the trailing stimulus. Leading stimuli that exceed the duration of the early processing phase produce no visible persistence at all, thus precluding integration with trailing stimuli. This account of the inverse-duration effect is obviously based on an SOA rule.

Also governed by an SOA rule is metacontrast masking (Di Lollo et al., 2004; Kahneman, 1967). Its temporal course is said to be governed by inhibitory interactions between transient and sustained visual pathways (Breitmeyer & Ganz, 1976). The transient channel has short latencies and carries spatial information. The sustained channel has longer latencies and carries information about stimulus identity. The onset of any given stimulus is said to activate both channels. To account for metacontrast masking, it is assumed that activation of the transient channel produces a brief burst of activity that inhibits ongoing activity in the sustained channel.

Increasing the duration of the target (i.e., increasing the target-mask SOA) generates the classical *U*-shaped metacontrast function. At short SOAs, little or no masking occurs because the transient burst produced by the mask has subsided before the onset of the sustained activity triggered by the target. Masking will occur at intermediate SOAs because the mask's transient burst occurs during the target's period of sustained activity and inhibits it. No masking will occur at long SOAs because the mask's transient burst occurs after the target's sustained activity has subsided and the processing of the target has been completed. Neurophysiological support for this inhibitory account has been provided by Breitmeyer (1984) and by Breitmeyer and Öğmen (2006).

There is a clear parallel between the inhibitory account of metacontrast masking and the temporal overlap of early-processing activity in temporal integration. In metacontrast masking both the leading stimulus (the target) and the trailing stimulus (the mask) are visible at short SOAs. This corresponds to temporal integration that is said to occur when the period of early sustained activity triggered by the two stimuli overlap in time. The important point is that the period over which temporal integration occurs (i.e., the inferred duration of visible persistence) can be explained in terms of the temporal course of the inhibitory interactions that occur in metacontrast masking.

The Inverse Intensity Effect

It has been known for some time that the duration of visible persistence varies inversely with stimulus intensity (Charpentier, 1887; Di Lollo, 1984; Hecht & Verrijp, 1933). An extensive review of findings and theories of the inverse intensity effect has been reported by Di Lollo and Bischof (1995) who singled out the *temporal impulse response function* as a prime determinant of metacontrast masking. The term "impulse response function" denotes the visual system's response to brief stimuli over a period of a few hundred ms. The function is biphasic: an initial positive (excitatory) phase is followed by a negative (inhibitory) phase. As stimulus intensity is decreased, the duration of the positive phase increases and the duration of the negative phase decreases (Sperling & Sondhi, 1968).

The duration of visible persistence can be represented by the duration of the positive phase of the response function. At high levels of luminance, the positive phase is as brief as 30 ms and is followed by a negative phase of less than 100 ms (Sperling & Sondhi, 1968). In the matrix task, this negative phase corresponds to the suppression of the internal representation of the leading frame, making it unavailable for integration with the contents of the trailing frame (Di Lollo & Bischof, 1995). In dark-adapted viewing, the duration of the positive phase is at a maximum and inhibitory processes are weak or absent (Di Lollo & Bischof, 1995; Ikeda, 1965; von Bèkèsy, 1968). Temporal integration is said to occur when the positive phase of the leading frame overlaps in time with the positive phase of the trailing frame.

As was the case for the inverse proximity and the inverse duration effects, the matrix task provides direct estimates not of the duration of visible persistence but of the period during which temporal integration can occur. Given our understanding of the factors that modulate temporal integration (proximity, duration, and intensity of the stimuli) it is appropriate to question the utility of the derivative concept of visible persistence as an explanatory basis for the observed inverse effects.

The inverse effect of additional contours

We have argued that estimates of the durations of visible persistence obtained with the matrix task are foreshortened by metacontrast masking. Implied in this claim is the expectation that any operation that reduces the strength of masking should result in a corresponding increment in the estimated duration of visible persistence.

Masking strength can be lowered not only by increasing the inter-dot separation or the luminance of the dots, as we have seen, but also by introducing additional contour lines in the display (Breitmeyer, 1978; Breitmeyer et al., 1981; Stoper & Banffy, 1977; Werner, 1935). On the hypothesis of a reciprocal relationship between strength of metacontrast masking and estimated duration of visible persistence, the introduction of additional contours should lead to longer estimates of visible persistence.

That is precisely what was found by Groner et al. (1990) who employed the matrix task in two display conditions. In one condition, the dots were embedded within the contours of a 5×5 grid, with one dot in each cell, except for the missing dot whose cell was empty. The other condition was the same except that the grid lines were omitted. The results were unambiguous: temporal integration occurred over significantly longer intervals (SOAs) when the grid was present. This outcome is entirely consistent with the hypothesis that the grid lines attenuated the inhibitory interactions inherent in metacontrast masking. Again, the enhanced temporal integration was mediated not by an increment in the duration of visible persistence per se, but by a decrement in the masking of the leading frame.

Concluding Remarks

The two-frame paradigm was first introduced by Eriksen and Collins in 1967 to study the duration of visible persistence. It was later developed into the dot-matrix paradigm by Hogben and di Lollo (1974). Since then, the dot-matrix paradigm has been used extensively to estimate the duration of visible persistence under diverse viewing conditions.

In the present work, we claim that, in a substantial number of cases, the matrix task yields an index not of the duration of visible persistence but of the period for which the leading frame escapes metacontrast masking by the trailing frame. From this perspective, it should be emphasized that metacontrast masking does not invalidate the measurement of visible persistence as such. However, those estimates need to be regarded as foreshortened by metacontrast masking: the stronger the masking, the greater the foreshortening.

Metacontrast masking can affect the accuracy of estimates obtained not only with the matrix task but also with other tasks in which stimuli are displayed sequentially. Typically, those studies were initially designed to examine the phenomenon of motion deblurring. For example, Hogben and Di Lollo (1985) employed a briefly-displayed aggregate of random dots that were perceived as in horizontal motion. To produce a sensation of motion the array was displayed repeatedly, with each point displaced a small horizontal distance from its previous location. Apparent velocity was manipulated by varying the inter-dot separation across conditions. Because of visible persistence, what was seen was not an aggregate of single dots displayed repeatedly on the screen, but a bunch of dotted lines in horizontal motion. Notably, the number of perceived dots in each line was related directly to inter-dot separation. This case of inverse-proximity effect parallels that obtained with the matrix task and invites a metacontrast-masking account of suppression of temporally-leading dots by temporally-trailing dots. The commonality of inverse-proximity effects causes the two paradigms to yield estimates of visible persistence that are foreshortened by metacontrast masking. Similar conclusions were reached by Di Lollo and Hogben (1985) who employed sequential displays of dots in apparent circular motion to study motion deblurring.

Given that metacontrast masking oppugns the accuracy of estimates obtained with paradigms in which the stimuli are displayed in close temporal sequences, are there more adequate ways to estimate the duration of visible persistence? One way that comes readily to mind is Sperling's (1960) paradigm in which a set of alphanumerical characters is displayed briefly on the screen. The observers' task is to report as many characters as possible. The paradigm comes in two versions: whole report (report as many characters as possible from the entire set) and partial report (report the characters in a subset of the array indicated by a temporally-trailing cue).

Sakitt (1976) used the whole report version with a dark-adapted observer and found that the contents of the display could be identified for as long as 10s after offset. The corresponding estimate of the duration of visible persistence is questionable on at least two grounds. First, it is possible that what was being measured was the duration of retinal afterimages instead of – or as well as – visible persistence. The two phenomena are known to differ from one another on several criteria (Di Lollo et al., 1988). Second, it is known that identification of individual stimuli such as alphanumerical characters gives rise to two forms of persistence: visible persistence and informational persistence (Di Lollo & Dixon, 1988; Phillips, 1974).

Visible and informational persistence have been found to differ from one another on a number of dimensions: visible persistence is time-locked to stimulus onset, has unlimited capacity, is susceptible to masking, and as far as we can measure it, is relatively brief (<150 ms). In contrast, informational persistence is time-locked to stimulus offset, is not susceptible to masking, has limited capacity, is relatively long-lasting (>500 ms) and, while maintaining some spatial information as well as a structural representation of the contents of the display, is no longer visible (Di Lollo & Dixon, 1988; Phillips, 1974; Turvey, 1978). The important point is that the two forms of persistence generated by a brief alphanumerical display are temporally overlapping and cannot be entirely disentangled from one another. This makes the Sperling task unsuitable for the measurement of visible persistence alone. Of course, this does not apply to the dot-matrix task. On the other hand, as we have seen, the dot-matrix task – along with related tasks, such as employed by Hogben and Di Lollo (1985) – are prone to metacontrast masking.

In summary, the job of estimating the duration of visible persistence is beset by two types of problems. First, at least some tasks involving the temporal integration of successive displays are prone to metacontrast masking. This causes them to underestimate the duration of visible persistence. Second, as we have just seen, tasks involving the report of identifiable stimuli such as alphanumerical characters, cannot disentangle visible from informational persistence.

It should be emphasized that the principal objective of the present work was not to develop for visible persistence the kind of high-precision measurements common in the world of physis. Rather, by highlighting the possible confounding effect of metacontrast masking, our intent was to point the way to more nuanced theoretical accounts of visible persistence. Current theories tend to ascribe the temporal integration of successive displays to a single underlying mechanism. For example, Duysens et al. (Duysens et al., 1985; but see Cork et al., 2020) have proposed that temporal integration occurs when the initial volley of neuronal firing triggered by the leading stimulus overlaps in time with that triggered by the trailing stimulus. The tenability of such unidimensional theory is questionable because it would require the dubious *ad-hoc* assumption that the duration of the initial volley of neuronal firing varies inversely with the spatial proximity of the stimuli. This is not to say that such unidimensional theories are necessarily incorrect: they are merely incomplete and should be augmented with considerations of additional factors such as metacontrast masking.

In the absence of methodological innovations, the best that can be done at present is to obtain estimates that are least affected by extraneous factors. For example, the influence of metacontrast masking in successive displays could be minimized – if not effectively eliminated – by implementing procedures that reduce masking strength: the matrix task would be performed in dark-adapted viewing, the dots would be dim, widely spaced, and would be displayed within a grid. This would probably yield estimates of visible persistence that are close to its true duration.

Authors' contributions The two authors contributed equally.

Funding This work was supported by Discovery Gants from the Natural Sciences and Engineering Research Council of Canada to TMS and to VDL.

Declarations

Conflicts of interest The authors have no conflicts of interest to declare that are relevant to the contents of this article.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Availability of data and materials No new data were acquired for this work.

Code availability Not applicable.

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