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Two visual targets for the price of one? Pupil dilation shows reduced mental effort through temporal integration

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ABSTRACT

In dynamic sensory environments, successive stimuli may be combined perceptually and represented as a single, comprehensive event by means of temporal integration. Such perceptual segmentation across time is intuitively plausible. However, the possible costs and benefits of temporal integration in perception remain underspecified. In the present study pupil dilation was analyzed as a measure of mental effort. Observers viewed either one or two successive targets amidst distractors in rapid serial visual presentation, which they were asked to identify. Pupil dilation was examined dependent on participants' report: Dilation associated with the report of a single target, of two targets, and of an integrated percept consisting of the features of both targets. There was a clear distinction between dilation observed for single-target reports and integrations on the one side, and two-target reports on the other. Regardless of report order, two-target reports produced increased pupil dilation, reflecting increased mental effort. The results thus suggested that temporal integration reduces mental effort and may thereby facilitate perceptual processing.

Keywords: temporal integration, mental effort, attention, working memory, pupil dilation, rapid serial visual presentation

Almost continuously, we receive visual input that needs to be processed by our brain to arrive at coherent percepts that can be evaluated and, if necessary, acted upon. Some percepts emerge quickly from this torrential stream. For instance, we are able to detect flickering in bright light at on/off cycles of less than 20 ms long (Hecht & Verrijp, 1933). It seems as if we nevertheless slow down considerably when more than such simple stimulus detection is needed. A visual stimulus needs to last about 70 ms before a human observer can reliably see whether it was longer than another of just 1 ms (Efron, 1967). This slower pace of perception allows us to perceive fluid motion when watching movies, even though these actually are slideshows of successive still images, each shown for about 42 ms.

To fully encode visual information, the brain may take as long as 150-300 ms (e.g., Rousselet, Macé, & Fabre-Thorpe, 2003; VanRullen & Thorpe, 2001). To prevent increasing processing lag as sensory input continues, we thus do not attempt to analyze that input in 20 ms slices, but instead let it accumulate across longer, meaningful intervals (cf. the perceptual moment; Allport, 1968), after which the sensory information within is passed on for further processing. This perceptual process of accumulation and combination of successive stimuli into a singular percept is called temporal integration, and is somewhat reminiscent of chunking in memory (Miller, 1956). Temporal integration has been observed with various stimuli in both vision (e.g., Eriksen & Collins, 1967; Hogben & Di Lollo, 1974) and audition (Saija, Andringa, Başkent, & Akyürek, 2014; Tervaniemi, Saarinen, Paavilainen, Danilova, & Näätänen, 1994), and it has been shown that integrated percepts start to form in the brain within 200 ms (Akyürek, Schubö, & Hommel, 2010).

In one view, temporal integration might be seen as a brief, passive buffer of fixed duration, which is maintained to cope with overflowing sensory input that the perceptual system struggles to keep up with. As such, it may reflect little more than perceptual processing latency (e.g., Di Lollo & Dixon, 1988). Alternatively, temporal integration may be viewed as a more adaptive process that may actually reduce perceptual effort. There is evidence for the adaptive part of that claim: The likelihood of temporal integration is modulated not only by exogenous factors such as stimulus luminance and spatial proximity (e.g., Di Lollo & Hogben, 1987; Long & Beaton, 1982), but also by endogenous factors such as expected presentation speed, the anticipated usefulness of integration, and the availability of attention (Akyürek, Toffanin, & Hommel, 2008; Forget, Buiatti, & Dehaene, 2010; Geerligs & Akyürek, 2012; Visser & Enns, 2001). However, there is no direct evidence yet that temporal integration might also facilitate perceptual processing.

There is some tentative support for a positive effect of integration from the attentional blink phenomenon. The attentional blink is elicited when observers search for two or more target stimuli, which are typically presented within a rapid serial visual presentation (RSVP) of distractors, and it reflects the difficulty of target identification when another target preceded it within less than about half a second (Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). Crucially, the blink can be avoided when the targets are presented in direct succession and close temporal proximity. In this so-called Lag 1 condition, identification performance of the second target is frequently spared from the blink, despite the apparent lack of time available (Potter, Chun, Banks, & Muckenhoupt, 1998; Visser, Bischof, & Di Lollo, 1999). Target order report errors are also strongly elevated at Lag 1, which has been taken as evidence for temporal integration of the targets, because their joint representation in a single event would explain the loss of order information (Hommel & Akyürek, 2005). Thus, integration may allow observers to improve their perception of both targets, although at the cost of temporal distinctiveness (i.e., target individuation), and without apparent benefits for subsequent selection (Dux, Wyble, Jolicœur, & Dell'Acqua, 2014).

This account remains tentative because order errors are an indirect measure of temporal integration. Temporal integration merges the features of the stimuli, resulting in a single, unified percept, but reporting such a percept is usually not possible in RSVP tasks. Akyürek and colleagues (2012) did show that when this option is given (e.g., reporting "X" when "/" and "\" were presented) participants indeed often did so at Lag 1. Although integration can thus be linked to enhanced feature identification, one might wonder whether effort is also reduced, or whether the successive presentation of the targets simply allows for the investment of more effort and thereby better performance.

Physiological findings have suggested that the effort invested in the processing of a first target influences the processing of subsequent stimuli. Wierda, Van Rijn, Taatgen, and Martens (2012) investigated mental effort in a two-target RSVP task by measuring pupil dilation. Pupil size has been shown to vary as function of task-induced mental effort (e.g., Beatty, 1982; Hess & Polt, 1964; Porter, Troscianko, & Gilchrist, 2007; Van Rijn, Dalenberg, Borst, & Sprenger, 2012) and upon target detection in visual tasks that require rapid perception (Privitera, Renninger, Carney, Klein, & Aguilar, 2010). Wierda and colleagues observed that when more effort was invested in the first target, the chances of reporting the second decreased.

In a similar study, Zylberberg, Olivia, and Sigman (2012) demonstrated that Lag 1 may be more costly in terms of mental effort overall than other lags. At Lag 1, where Zylberberg and colleagues (2012) observed sparing behaviorally, they found that the pupil was more dilated than at later, blink-affected lags. It is conceivable that this effort might be related to the presence of target competition at Lag 1, which affords the report of one target only at the expense of the other (Potter, Staub, & O'Connor, 2002). Alternatively, because integration is frequent at Lag 1, it may be tempting to take this evidence of *increased* mental effort as an indicator for the cost of integration. However, this again remains speculative, because the study could not discriminate integration from other processes at Lag 1.

The present study

Whether temporal integration can reduce effort and thereby facilitate perceptual processing thus remains unclear. The present study sought to address this issue by measuring pupil dilation in an RSVP task that enabled the report of integrated percepts (cf. Akyürek et al., 2012). To assess the mental effort involved in target processing, pupil dilation was calculated across physically identical stimulus conditions at Lag 1, dependent on the behavioral outcome: The correct report of a single target, of two targets (either order-correct or with an order error), of a single integrated percept (and nothing else), and of trials in which only the first of two targets was reported (T2-missed trials, as in an attentional blink). Crucially, if temporal integration reduces mental effort, then pupil dilation associated with a single integrated percept should be less than dilation observed in trials in which the same stimulus information was presented and processed, but not integrated (i.e., two-target reports).

Method

Participants

Thirty-one first-year psychology students (23 females) of the University of Groningen participated in the experiment for course credits. All participants gave written consent and the study was approved by the departmental ethical committee. Mean age was 20.4 years (range 18-29 years) and all participants reported normal vision. One participant was excluded from all analyses because of unusually low single-target performance (below 30%).

Apparatus and stimuli

Stimulus presentation was controlled with PST E-Prime 2.0 Professional and presented at a 100 Hz refresh rate at a resolution of 1920 x 1080 on a 27" Iiyama G2773HS

LCD, which was calibrated with a high-speed camera. Eye movements and pupil dilation were sampled at 1000 Hz using an EyeLink 1000 with 0.01° spatial resolution. The distances between the monitor and the chinrest, and the eye-tracker and the chinrest were kept constant at 64 cm and 45 cm, respectively. A USB mouse was used for response input.

The target stimuli consisted of a line tilted 45° rightward, a line tilted 45° leftward, and a square with rounded corners, as well as any possible combination of two or three of these features, resulting in a total of 7 unique symbols. All lines were 6 pixels thick. The square subtended 60x60 pixels (1.81° of visual angle) and the diagonal lines fitted in a box of 44x44 pixels. The lines were separated from the rounded corners of the square by a gap of 2 pixels when presented together.

For two-target trials, the possible number of target pairs that can be created without using a particular feature twice is 6 (note that the target containing all three features cannot be used during two-target trials), which can also be presented in reversed order to make 12 unique pairs. To increase the relative proportion of two-target trials, each of these pairs was presented twice. The combined total of 31 trials (24 two-target trials and 7 one-target trials) was repeated 9 times, resulting in 279 trials in total.

Procedure and design

The trial outline is depicted in Figure 1. Each trial was initiated by a mouse click after which a fixation cross at the center of the screen was shown for 900 ms. An RSVP of 19 stimuli followed, each of which was on screen for 70 ms and followed by a 10 ms blank screen. The distractor stimuli were randomly selected capital letters (Courier New Bold 52pt, matched in size to the targets). The first target (T1) was presented at the 7^{th}, 8^{th}, or 9^{th} position, with the second target (T2) presented immediately after the first (i.e., at Lag 1) in two-target trials.

insert Figure 1 about here

After RSVP offset, a blank screen was shown for a random duration between 1400-1800 ms, after which the first response screen appeared. The response screen contained all seven possible targets presented in a circle, with the mouse cursor set to the circle's midpoint. Participants were asked to click on the target that they thought to have seen as the first target. On the second response screen, participants were asked to indicate which target they saw as the second target. One of the response options was an empty square, which the participants were asked to click if no second target was detected. The experiment consisted of three blocks within which one- and two-target trials were randomly intermixed, separated by participant-paced breaks. The entire experiment lasted about 50 minutes.

Results

Participants responded correctly in 80.7% (*SD* = 15.0%) of the one-target trials. Within the two-target condition, both targets were reported in the correct order in 21.3% (*SD* = 13.6%), and in the inverse order in 12.3% (*SD* = 8.9%) of trials. A single target consisting of the merged features of both presented targets (temporal integration) was reported in 18.0% (*SD* = 16.2%), and only the first of the two targets (as in an attentional blink) in 15.3% (*SD* = 6.3%) of trials. All other missed target trials and trials for which features were selected that were not presented were excluded from subsequent analyses.

The raw pupillary data were down-sampled to 100 Hz and split into segments of 5000 ms for each trial, time-locked to T1 onset (-1500 ms to 3500 ms). Eye-blinks were corrected using linear interpolation. The average pupil size between -100 ms to 0 ms was used as a baseline. The reported pupil dilation is the proportional difference relative to this baseline. The resulting pupillary responses are shown in Figure 2.

insert Figure 2 about here

As the final number of trials per condition and participant fluctuates as a function of task performance, traditional ANOVAs are less suited. We therefore report analyses based on linear-mixed effect models (*lme4*, Bates, Maechler, Bolker & Walker, 2013) that are less affected by trial number fluctuations. All analyses focused on the average pupil dilation from T1 onset until the earliest possible presentation of the first response screen (0-2200 ms), assessing the contribution of the fixed effects of trial condition (1 or 2 targets presented), and, for the two target condition, the contributions of order error, T2-missed, and integration trials on the proportional pupillary response. As random effects, subject and by-subject random slopes for the effect of trial condition were included. For each fixed effect, we will report estimate coefficients and standard errors, and the associated *t*-value. As suggested by Bates et al. (2013), *p*-values were obtained where possible by likelihood-ratio tests of the full model against the model without the effect in question.

A first analysis that tested whether trial condition had an overall effect on pupillary response, without taking into account how participants responded to the two-target condition, showed that the two-target condition is associated with a larger pupillary response ($\beta = 0.009$, $SE = 0.002$, $t = 3.788$, $\chi^2(1) = 12.115$, $p < 0.001$). However, as Figure 2 shows, the influence of the two-target condition is largely modulated by the behavioral response. This is reflected in the full model analyses. Compared to an intercept reflecting a pupillary increase of approximately 4% in the one-target condition ($\beta = 0.039$, $SE = 0.006$, $t = 6.929$), trials with two correct responses to the two-target condition are estimated to result in an increase in pupillary response by ~1.4% ($\beta = 0.014$, $SE = 0.003$, $t = 5.176$). Interestingly, no effect was found for order errors on pupil dilation ($\beta = 0.001$, $SE = 0.003$, $t = 0.371$, $\chi^2(1) = 0.134$, $p = 0.714$), but both integration ($\beta = -0.012$, $SE = 0.003$, $t = -4.379$, $\chi^2(1) = 19.164$, $p < 0.001$) and T2-missed trials ($\beta = -0.008$, $SE = 0.003$, $t = -3.204$, $\chi^2(1) = 10.277$, $p = 0.001$) resulted in a markedly reduced pupil dilation compared to the other two-target conditions.

To assess whether integration and T2-missed trials, in which participants responded with just a single one response, resulted in different pupillary responses than correct one-target trials, a second model was tested that included fixed effects of the number of reported targets, which could be either two (correct order and order error trials) or one (one-target correct, integration, and T2-missed trials), and factors encoding integration, T2-missed and order errors, and random effects of subject and by-subject random slopes for the effect of number of responses. Compared to an intercept reflecting a pupillary increase of approximately 4% in the one-target correct condition ($ß = 0.039$, $SE = 0.006$, $t = 6.227$), trials with two correct responses are estimated to result in an increase in pupillary response by ~1.5% ($ß = 0.015$, $SE = 0.003$, $t = 5.022$). As in the previous analysis, no effect was found for order errors on pupil dilation ($ß = 0.001$, $SE = 0.003$, $t = 0.349$, $\chi^2(1) = 0.121$, $p = 0.728$). However, unlike the previous analysis, here integration ($ß = 0.003$, $SE = 0.002$, $t = 1.398$, $\chi^2(1) = 1.915$, $p = 0.166$) did not result in an increased pupillary response, and T2-missed trials resulted in an increased response ($ß = 0.007$, $SE = 0.002$, $t = 2.762$, $\chi^2(1) = 7.585$, $p = 0.006$).

To meaningfully interpret the null results presented above, we computed Bayes factors (Rouder, Morey, Speckman, & Province, 2012) for the predictors by dividing the Bayes factors of a model with and a model without each predictor using the BayesFactor package (v0.9.5, Morey & Rouder, 2013). As the analysis requires at least a single observation per cell, two participants were excluded from further analyses. A comparison between a model that included the number of reported targets, integration, T2-missed, and order error with subject as random effect, versus a similar model without the effect of order error yielded a Bayes factor of 16.304 (±13.85%), indicating that it is 16 times more likely that an order error does not influence pupil dilation compared to two correct responses. Similarly for the one-target report trials, a model that excluded the effect of integration (thus not distinguishing between a one-target response after the presentation of a single target and a one-target response that was the integration of two presented targets) was clearly preferred over a full model (Bayes factor 5.822; ±2.2%). The preference for the simpler model was even stronger when a full model was compared to a model that excluded both integration and order error (Bayes factor 101.342; ±2.02%). These Bayesian analyses thus provided evidence that pupil dilation in integration and order error trials was not different from one-target and correctly ordered two-target trials, respectively.

DISCUSSION

The present study investigated whether temporal integration reduces mental effort and facilitates perceptual processing by examining pupil dilation at Lag 1 in an RSVP task. The pupillary response was differentially examined for integrations, correct two-target reports, order reversals, T2-missed, and correct single-target reports. The results provided compelling evidence that temporal integration reduces the mental effort required for perceptual processing: Pupil dilation elicited by two temporally integrated visual targets was markedly reduced compared to the dilation elicited by two separately perceived targets. This was observed despite the fact that the same visual features were represented in both cases, namely those of both targets. This finding stands in contrast with inferences that might have been drawn from consideration of the undifferentiated pupillary response to two targets at Lag 1 (Zylberberg et al., 2012). The increased dilation observed by Zylberberg and colleagues might thus at least in part be attributed to target competition effects, which are reduced when targets are temporally integrated, as in the present study (see also, Hommel & Akyürek, 2005).

There was furthermore evidence that the pupillary response in trials with integrations and with correct single-target reports is the same. The detection and encoding of two temporally integrated stimuli thus appears to be as effortful as that of a single stimulus. This conclusion may appear to be at odds with previous results showing that integration may draw upon attentional resources (Visser & Enns, 2001). A possible explanation may be that this attentional dependency is too small to be observed in pupillary responses. Akyürek and Meijerink (2012) found that in integration trials the N2pc component of the event-related potential (which has been linked to attentional selectivity; e.g., Eimer, 1996; Kiss, van Velzen, & Eimer, 2008) was similar to that of non-integration trials, although it developed somewhat later. Attentional deployment during integration may thus be only slightly different from single-target perception, and thereby not necessarily more demanding in terms of mental effort. It is furthermore possible that the pupillary response is influenced more by processes further downstream in the perceptual hierarchy, such as consolidation in (working) memory. Follow-up studies are planned to dissociate the effects of temporal integration on the efficiency of memory consolidation and attentional selection (cf. Dux et al., 2014).

Trials in which T2 was missed resulted in a pupillary response in-between the responses for two-target and the other single-target report trials, similar to previous observations (Zylberberg et al., 2012). This suggests that observers might have attempted to attend to the second target separately from and in addition to the first but failed to do so. Even though only a single target was eventually reported, their failed attempt thus still required increased effort. Alternatively, more resources might have been invested in T1 processing, leaving not enough for T2 (Wierda et al., 2014).

Finally, the present study allowed the measurement of pupil dilation when ‘true’ order errors were committed (note that in classic studies order errors and integrations are heaped together under the former term; Akyürek et al., 2012). Pupil dilation in response to order errors was statistically equivalent to the level of fully correct two-target reports, indicating that the retention of the correct stimulus order does not correlate with increased mental effort. Order errors may be committed due to prior entry; an attentional enhancement of the second target that leads to the misperception that it came first (Olivers, Hilkenmeier, & Scharlau, 2011), but the current pupil dilation measure did not seem to reflect such an effect.

Conclusion

The observation that mental effort is reduced through temporal integration reinforces the notion that it does not merely reflect perceptual latency. When the circumstances are right, when the features of multiple, successive stimuli can be adequately represented within a single extended event, temporal integration enhances perceptual efficiency by reducing mental effort. When such an extended event is not an optimal representation of the sensory input, when it is necessary to segregate and order the stimuli, this reduced effectiveness of the integrated percept should nevertheless be weighed against the gains in terms of effort. Overall, by virtue of the somewhat slower, but more efficient segmentation of the perceptual timeline it provides, temporal integration appears to be a key element in the perception of dynamic, ongoing sensory input.

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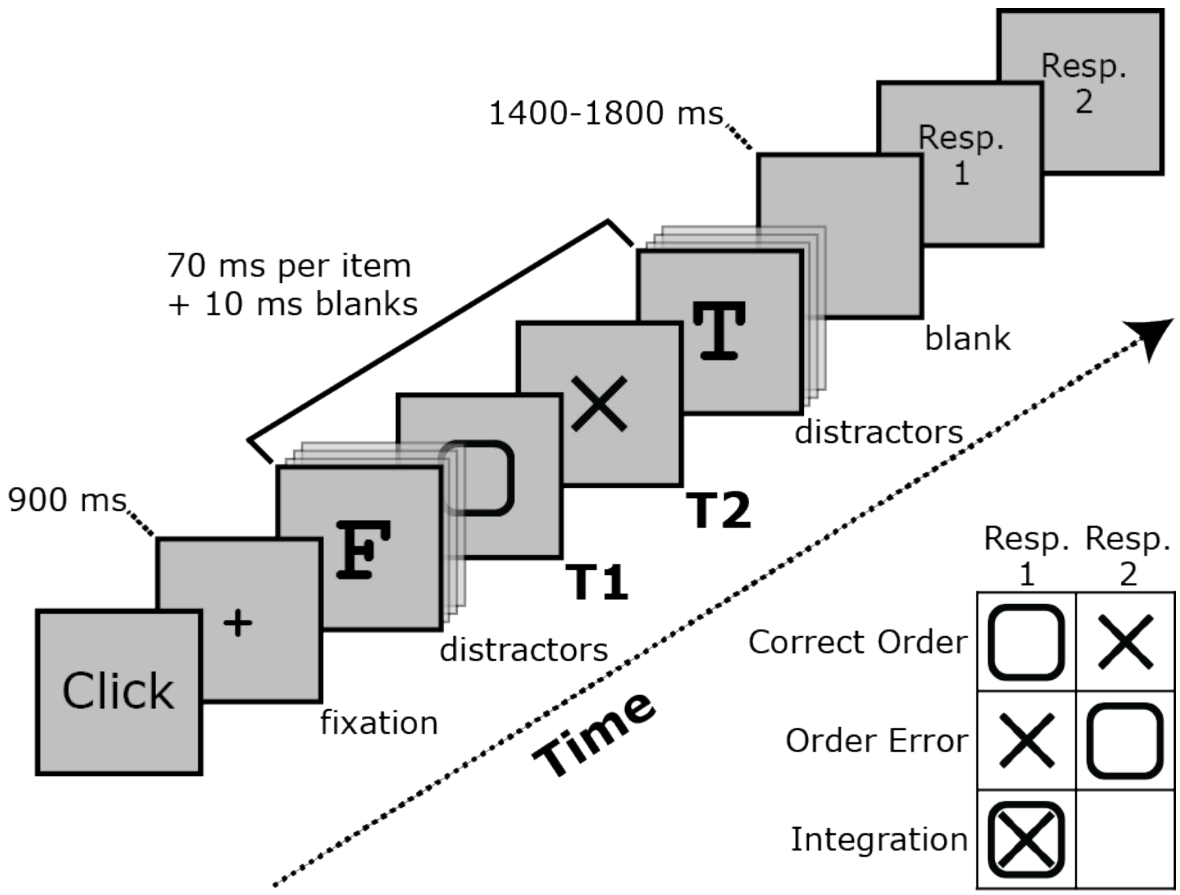
FIGURE CAPTIONS

Figure 1: Experimental procedure and design. After trial onset, a variable number of letter distractors appeared (depicted as transparent frames), after which one or two targets appeared in the stream (a two-target trial is shown), followed by several distractor letters. Targets consisted of single presentations and non-overlapping combinations of three features (a square outline and left- and right-tilted line segments at 45°). Stimuli lasted for 70 ms each, separated by a 10 ms blank interval. The inset table shows possible responses for the two depicted targets, including the integrated percept (partial, single-target responses not shown).

Figure 2: Pupil dilation (proportional increase) time-locked to T1-onset as a function of time, plotted separately for correct one-target trials (thin black line), integrations (thick grey line), T2-missed trials (dashed grey line), correctly ordered two-target trials (thick black line), and incorrectly ordered two-target trials (dashed black line).

Figure 1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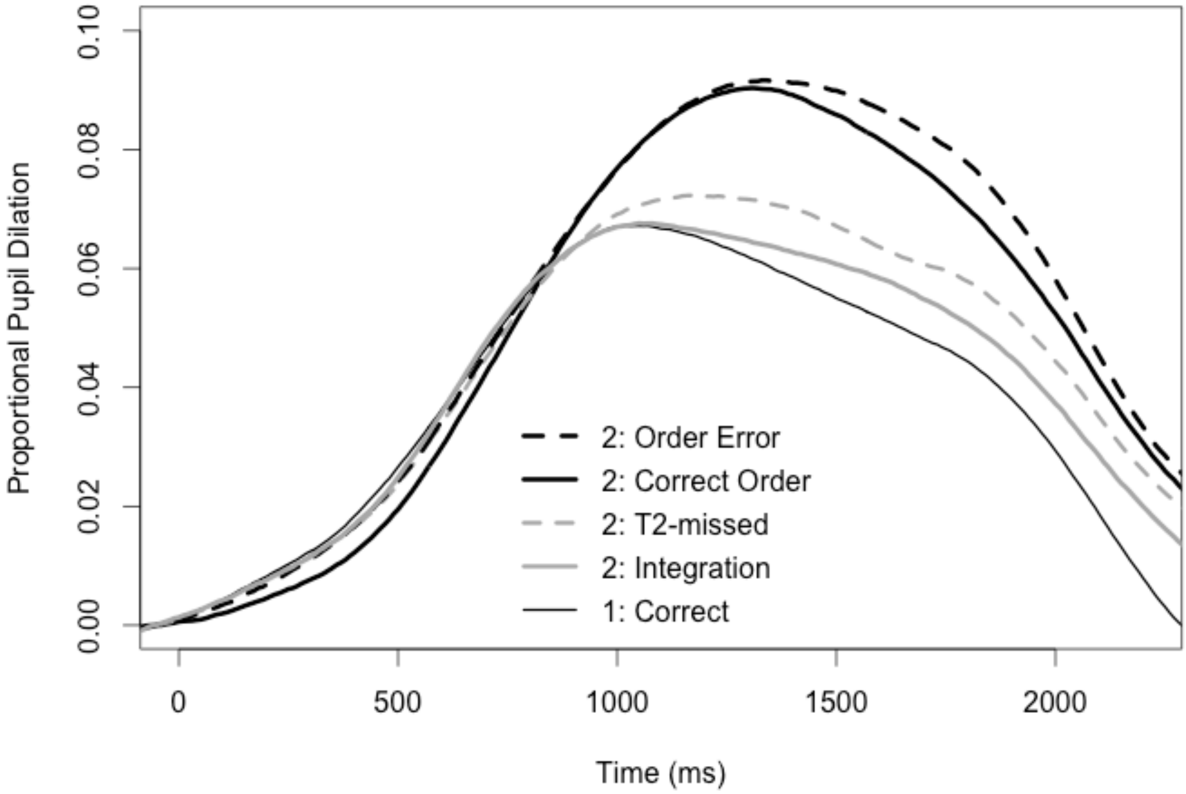
Integration

Figure 2


Proportional Pupil Dilation
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0.08
0.10
0
500
1000
1500
2000
Time (ms)
2: Order Error
2: Correct Order
2: T2-missed
2: Integration
1: Correct