Individual differences in the temporal dynamics of attentional selection

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Author Note

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Abstract

Attention can be focused on specific locations in our visual field (space-based attention), but also spreads along objects (object-based attention). However, the effects of object-based attention are not as prevalent as effects of space-based attention and prone to large individual differences. Here we investigated whether the low prevalence of object-based effects is related to individual differences in the temporal dynamics of attentional selection. In a two-rectangle discrimination task, we manipulated cue-to-target intervals from 50 to 600 ms. Space- and object-based effects were measured on group level and for individual participants. We used bootstrapping to highlight cue-to-target intervals with maximal space- and object-based effects, and fast Fourier transform (FFT) to investigate the rhythmic sampling of locations within and between objects. Whereas overall, space-based effects were robust and stable across all cue-to-target intervals for most participants, object-based effects were small and were only found for a small subset of participants. In the frequency domain, we did not observe rhythmic sampling at locations within and between objects, and only a few participants showed significant periodicities. Our findings confirm inter-individual variability in the temporal dynamics of object-based effects and emphasize the importance of considering individual variations in theories on visual attention.

Keywords: object-based attention, space-based attention, individual differences, rhythmic sampling, sustained attention, spatial attention

Introduction

When we open our eyes, a manifold of visual information enters simultaneously. There is no limit to the amount of incoming information at this early stage of visual processing. However, the brain does not possess an unlimited capacity to process it all at the same time, and different types of attention aid the selection of relevant information. For example, attention can be allocated to a spatial location in the visual field (Posner et al., 1980). This so-called *space-based attention* improves the processing of information in the attended region. *Object-based attention*, in comparison, directs attention to specific objects in visual space. For object-based attention, all parts of the attended object are thought to be processed simultaneously and the processing of parts within an attended object is faster than processing parts across different objects (Duncan, 1984; Egly et al., 1994; Moore et al., 1998; Richard et al., 2008).

In a commonly used paradigm to study space- and object-based effects, two rectangular objects are presented horizontally or vertically on the screen. A cue appears at one end of one rectangle, shortly followed by a target. The target can appear at the same location as the cue (*valid trials*) or at uncued locations, either at the far end of the cued rectangle (*invalid same-object trials*) or at the near end of the uncued rectangle (*invalid different-object trials*). Participants are asked to detect or discriminate the target as quickly as possible. Most importantly, the cue is equidistant from the target on both types of invalid trials. Interestingly, however, object-specific advantages are commonly shown by faster responses on the same- compared to different-object trials, which indicates that attention spreads along the object. This paradigm, and modified versions of it, have been widely used to study space- and object-based attentional selection (Egly et al., 1994; Moore et al., 1998; Pilz et al., 2012; Nah et al., 2018).

In general, object-based effects have been found to be smaller and not as robust as space-based effects (Brown & Denney, 2007; Hecht & Vecera, 2007), and are affected by changes to the paradigm, including the probability of targets appearing at the cued location (Chou & Yeh, 2018; He et al., 2004; Nah & Shomstein, 2020) and the duration of the interval between the cue and the target

(Chou & Yeh, 2018; Drummond & Shomstein, 2010; Shomstein & Yantis, 2004). Testing 240 participants, Pilz et al. (2012) investigated the strength of space- and object-based effects on the level of individual participants. Overall, they observed large inter-individual variability for both space- and object-based effects. But whereas space-based effects were large and were found in nearly all participants across three conventional paradigms (Egly et al., 1994; Moore et al., 1998; Watson & Kramer, 1999), object-based effects were small and only present in a minority of participants.

Here, we investigate whether the low prevalence of object-based effects is related to individual differences in the temporal dynamics of attentional selection. Several studies have found that the length of cue-to-target intervals modulates object-based attention such that the magnitude of object-based effects declines with an increasing cue-to-target interval (Chou & Yeh, 2018; Drummond & Shomstein, 2010; Shomstein & Yantis, 2004). More recently, Helfrich et al. (2018) showed that object-based attention fluctuates over periods of 500–1700 ms in behavioral performance, and that this fluctuation is shaped by neural oscillations. Further, individual differences have previously not only been found for object-based attentional selection but also for other attentional processes (Huang et al., 2012; Meyerhoff & Papenmeier, 2020), in particular, in the temporal domain related to the attentional blink (Willems et al., 2013, 2016). Therefore, it is reasonable to assume that the cue-to-target interval at which maximal object-based effects occurs, differs on an individual basis. To test our hypothesis, we adopted the commonly used two-rectangle discrimination task described above (Moore et al., 1998; Pilz et al., 2012). Instead of a consistent cue-to-target interval of 200 ms, we systematically changed intervals from 50 ms to 600 ms to assess object-based effects over time.

Our hypothesis ties in with research that suggests visual attention to be a rhythmic rather than a continuous process. Attention samples the environment in a particular frequency that leads to an either enhanced or diminished perceptual sensitivity of location within the visual field (Chakravarthi & VanRullen, 2012; Fiebelkorn & Kastner, 2019; Landau & Fries, 2012; Vanrullen, 2013). Attentional rhythms in the theta (4–8 Hz) frequency range have been found in different studies

related to attentional cueing, stimulus detection, and visual search (Busch et al., 2009; Dugué et al., 2015, 2016; Fiebelkorn et al., 2013; Landau & Fries, 2012; Re et al., 2019; VanRullen, 2016; VanRullen et al., 2007). Moreover, Fiebelkorn et al. (2013) investigated rhythmic sampling of attentional selection in behavior and confirmed rhythmic patterns of space- (at 8 Hz) and object-based attention (at 4 Hz).

To investigate whether the low prevalence of object-based effects is related to individual differences in the temporal dynamics of attentional selection, we measured attentional selection in the time and the frequency domain on both group- and subject-level. Given that object-based effects commonly occur at intervals between 100 ms and 400 ms, we decided to test performance for cue-to-target intervals between 50 ms and 600 ms, rather than between 300 ms and 1000 ms, as done in previous studies (Fiebelkorn et al., 2013; Helfrich et al., 2018; Landau & Fries, 2012; Song et al., 2014). In the time domain, we first assessed overall object-based effects across time using parametric statistical methods (i.e., ANOVA and t-tests). We then used a non-parametric bootstrapping method, similar to Pilz et al. (2012), to assess the temporal dynamics of space- and object-based effects for each participant. In the frequency domain, rhythmic patterns of space- and object-based attention were measured by assessing the periodicities of attended locations using the Fast Fourier Transform (FFT), similar to the methods described by Fiebelkorn et al. (2013).

Methods

1.1 Participants

Forty-seven undergraduate students were recruited from the University of Groningen to participate in this experiment in exchange for course credits. Four participants were excluded from the analysis: two participants quit during the experiment, one participant pressed repetitive keys for more than half of the trials, and one participant had a visual acuity below 0.8 (measured by the Early Treatment Diabetic Retinopathy Study logarithmic vision chart; Told, Baratsits, Garhöfer, & Schmetterer, 2013). The final sample comprised data of forty-three participants (18–27 years, $M = 19.9$; $SD = 1.7$, 12 males) with normal or corrected-to-normal visual acuity. The Ethical Committee

Psychology of the University of Groningen approved the experiment and procedures. All participants gave written informed consent, and the experiment was conducted in accordance with the Declaration of Helsinki.

1.2 Apparatus, Stimuli, and Procedure

All stimuli and experimental trials were created using MATLAB 9.5 (The MathWorks) and the Psychophysics toolbox version 3.0.16 (Brainard, 1997; Kleiner et al., n.d.) running under Windows 10 and displayed on a 1920 × 1080 monitor with a refresh rate of 100 Hz. Participants viewed the stimuli binocularly at a distance of 57 cm while seated in an adjustable chair in a darkened room.

Stimuli and procedure were similar as in the discrimination task from Pilz, Roggeveen, Creighton, Bennett, & Sekuler (2012) and Moore, Yantis, & Vaughan (1998). The stimulus display was composed of two white rectangles (each 1.6 × 8.2 degrees visual angle) and a white fixation cross (0.45 × 0.45 degrees visual angle) located in the center of the screen. The background of the display was grey (Figure 1). The two rectangles were oriented horizontally and located above and below the fixation cross. Object-based effects were found to be more prominent for horizontal objects (Al-Janabi & Greenberg, 2016; Barnas & Greenberg, 2016; Hein et al., 2017; Pilz et al., 2012). Given the emphasis on temporal aspects of object-based attention and the duration of the experiment, only horizontal objects were included in the current study.

At the start of each trial, two rectangles were presented for 1000 ms on the screen. A red square cue (1.6 × 1.6 degrees visual angle) was then presented for 100 ms in one of the four corners of the two rectangles. Following a randomly sampled 50–600 ms cue-to-target interval (in steps of 10 ms, corresponding to a sampling frequency of 100 Hz), one target and three distractors appeared. The target was presented in one of three locations: the cued location (*valid trials*), the opposite end of the cued rectangle (*invalid-same trials*), or the same end of the uncued rectangle (*invalid-different trials*). Targets were either a letter T or a letter L, presented with equal probability in an upright orientation, or rotated 90, 180, or 270 degrees. Distractor items were T-L hybrid characters, which had the same size as the target items and were also presented in one of the four orientations (0, 90,

180, and 270 degrees). Participants were asked to identify whether the target was a “T” or an “L” by pressing the “/” key (for T’s) or the “z” key (for L’s) on a QWERTY keyboard as quickly and accurately as possible. The target and distractors stayed on the screen until the participant made a response. Each participant completed 32 blocks with 50 trials, 1600 trials in total, of which 80% were valid trials, 10% were invalid-same trials, and 10% were invalid-different trials. Fifteen practice trials were provided for participants to familiarize themselves with the task before starting the experiment.

Figure 1. Schematic diagram of one trial sequence for each of the three conditions.

1.3 Analysis

Following Moore et al. (1998) and Pilz et al. (2012), reaction times of less than 150 ms were excluded as anticipatory responses, and only correct responses were included in the analysis.

To estimate space- and object-based effects over time, we calculated mean reaction times (RT) for valid, invalid-same, and invalid-different trials within 51 bins of 50 ms. Starting with the cue-to-target interval of 50–100 ms, the 50-ms bin was shifted forward by 10 ms to calculate the next reaction time average (60–110 ms). This procedure was repeated across the whole range of cue-to-target intervals from 50 ms to 600 ms.

Space-based effects were calculated by subtracting the mean RTs of valid trials from the mean RTs of invalid trials for each cue-to-target interval. Object-based effects were calculated by subtracting the mean RTs of invalid-same trials from those of invalid-different trials for each cue-to-target interval. We conducted a 51 (cue-to-target interval) x 3 (valid, invalid-same, invalid-different)

repeated measures ANOVA to assess overall RT differences. FDR corrected t-tests were used to examine whether the cueing effects were greater than zero for each cue-to-target interval (Benjamini & Hochberg, 1995). Alternatively, computing space-based effects by subtracting the mean RTs of valid from those of invalid-different trials (e.g., Fiebelkorn et al., 2013) yielded nearly identical results to computing space-based effects by subtracting the mean RTs of valid from those of invalid trials. We decided to keep to the latter in the current study, as it is more common within the literature (Egley et al., 1994; Moore et al., 1998; Pilz et al., 2012). On the accuracy of responses, we followed the same data processing steps as described above. Because of the high accuracy in our task (Supplemental Figure S1a), analyses on individual differences and the rhythmic sampling of visual space were only based on RTs.

To investigate individual differences, we assessed space- and object-based effects for each cue-to-target interval for each participant using the percentile bootstrap method (Efron, 1992; Efron & Tibshirani, 1993; Mooney et al., 1993; Pilz et al., 2012). For each participant and each condition, 999 bootstrapped data sets were constructed by randomly resampling the original data with replacement. The bootstrapped data sets contained the same number of trials in each condition as the original data. Each bootstrapped data set was analyzed like the original sample: space-based effects were calculated by subtracting the mean bootstrapped RTs of valid trials from the mean bootstrapped RTs of invalid trials. Object-based effects were calculated by subtracting the mean bootstrapped RTs of invalid-same trials from those of invalid-different trials. The 2.5 and 97.5 percentiles of the bootstrapped cueing effects were used to estimate the 95% confidence intervals for space- and object-based effects for each cue-to-target interval.

For the spectral analysis, the data from each participant were standardized for each condition to a mean of zero and a standard deviation of one. After applying a Hanning window of the same length as the data, we converted the standardized time-series data into the frequency domain using the fast Fourier transform (FFT). The FFT was carried out only on the actual time points measured (without any zero padding), yielding a lower frequency limit and frequency resolution of 1.96 Hz. The

magnitudes of the FFT output were averaged across participants to estimate the average spectrum for each condition. Non-parametric statistical tests were applied to estimate the spectral significance. The non-parametric tests were computed as follows: for each participant and each condition, standardized RTs were resampled across cue-to-target intervals without replacement. The same data processing steps as for the original data (described above) were then applied to the randomized data. For each participant, this procedure was repeated 1000 times to generate reference distributions for each condition. The resulting spectra were then averaged across participants yielding 1000 average spectra for each condition. To determine the statistical significance of the frequency component, for each participant, the spectrum of each condition was compared with 1000 spectra of that condition respectively. On the group level, the average spectrum of each condition was compared with the 1000 average spectra of each condition respectively. P-values were the proportion of spectra in the reference distribution that exceeds the spectrum in the original data. P-values were corrected using the false discovery rate (FDR; Benjamini & Hochberg, 1995).

2. Results

Accuracy was overall high for all three conditions (valid: 96%, invalid-same: 89%, invalid-different: 90%) with significant space-based effects across all cue-to-target intervals but no significant object-based effects. Details can be found in the Supplemental Information and Figure S1.

2.1 Overall RTs

Figure 2a shows average RTs for all three conditions across cue-to-target intervals. The ANOVA showed a significant main effect of condition, $F(2, 84) = 138.49, p < 0.001, \eta_p^2 = 0.77$. Participants responded fastest for valid trials ($M = 555, SD = 7$), and faster for invalid-same trials ($M = 691, SD = 9$) than for invalid-different trials ($M = 726, SD = 9$). The main effect of cue-to-target interval was significant, $F(50, 2100) = 2.14, p < 0.001, \eta_p^2 = 0.05$. RTs varied between cue-to-target intervals with maximum RTs at the interval of 50 ms and minimum RTs at the interval of 300 ms. The interaction between condition and cue-to-target intervals was not significant, $F(100, 4200) = 1.62, p =$

0.09, $\eta_p^2 = 0.04$.

FDR corrected t-tests results showed significant space-based effects for all cue-to-target intervals: participants overall responded faster when targets appeared at cued locations than at uncued locations. Object-based effects were less pronounced than space-based effects, and were only significant at cue-to-target intervals between 130–190 ms, 230–260 ms, 280–360 ms, 380–390 ms, and 500–530 ms (Figure 2b).

We further compared individual standard deviations of the temporal dynamics between space- and object-based effects using paired t-tests. Inter-individual variations of the temporal dynamics for the object-based effects were significantly greater than those for space-based effects, $t(42) = 9.23$, $p < 0.001$.

Figure 2. a) Mean RTs $\pm$ SEM (standard error from the mean) for valid (blue), invalid-same (yellow), and invalid-different trials (red) for all cue-to-target intervals. b) Space-based effects (green line) and object-based effects (orange line) for all cue-to-target intervals. Filled dots showed cue-to-target intervals with significant effects.

2.2 Bootstrapping of individual participants

Figure 3 shows bootstrapped space- and object-based effects for individual participants at each cue-to-target interval (Figure 3a and 3b) and highlights the number of participants with significant space- and object-based effects for each cue-to-target interval (Figure 3c). Within each cue-to-target interval, more than 70% of the participants showed significant space-based effects. Moreover, twenty-three participants (53%) exhibited significant space-based effects for all cue-to-target intervals, twenty-seven participants (63%) exhibited significant space-based effects for more

than 90% of all cue-to-target intervals. Thirty-eight participants (88%) showed significant space-based effects for more than half of the cue-to-target intervals. Only one participant did not exhibit any significant space-based effects.

Object-based effects were not as prevalent as space-based effects. Maximum prevalence was shown at cue-to-target intervals from 210 to 340 ms (Figure 3c). Using t-tests, we further compared the percentage of participants showing significant effects between space- and object-based effects. Space-based effects were significantly more prevalent than object-based effects, $t(50) = 75.44$, $p < 0.001$. On the level of individual participants (Figure 3b), none of the participants exhibited object-based effects for all cue-to-target intervals. Forty participants (93%) exhibited object-based effects for more than one cue-to-target interval. Thirty-three participants (77%) exhibited significant object-based effects for less than ten cue-to-target intervals. Only three participants (7%) did not exhibit any significant object-based effects. Besides, significant reversed object-based effects (different-object advantage) were found in fifteen participants (35%). Supplemental Figure S2 shows space- (a) and object-based effects (b) for a subset of individual participants. We also calculated bootstrapped space- and object-based effects for data in which we subsampled the number of valid trials to be equal to the number of invalid same and different trials. Results did not differ significantly from the original analysis and are highlighted in Supplemental Figure S3.

Figure 3. Bootstrapped space- (a) and object-based effects (b) for individual participants. Black dots indicate cue-to-target intervals with significant bootstrapped effects. White dots indicate cue-to-target intervals with significant reversed object-based effects (different-object advantage). c) The percentage of participants with significant space- (green bars), object- (orange bars), and reversed object-based effects (white bars) in reaction times for each cue-to-target interval. The average percentage of space- (84%) and object- (11%) and reversed object-based effects (2%) are indicated by a green/black line, an orange/black line, and a white/black line, respectively.

2.3 Rhythmic sampling

Figure 4a shows the average amplitude spectrum for cued locations (valid trials), same-object locations (invalid-same trials), and different-object locations (invalid-different trials) across participants. No significant spectral amplitudes (FDR corrected) were found for frequencies of 4–10 Hz. On the individual level, few participants showed periodicity of 4, 6, 8 or 10 Hz for cued locations ($N \leq 4$; $<10\%$), same-object locations ($N \leq 4$; $<10\%$) and different-object locations ($N \leq 5$; $<12\%$).

Figure 4b shows the percentage of participants with significant amplitudes for three locations at frequencies of 4–10 Hz.

Figure 4. a) Average spectral amplitudes (mean $\pm$ SEM) for cued location (blue), same-object location (yellow) and different-object location (red). b) Percentage of participants with significant amplitudes for cued location (blue), same- (yellow), and different-object location (red) at frequencies of 4–10 Hz.

3. Discussion

Recent research has shown effects of object-based attention are smaller and less prevalent than effects of space-based attention, which are only found in a small subset of participants (Pilz et al., 2012). In the current study, we systematically manipulated intervals between the cue and the target from 50 to 600 ms. We investigated whether individual differences in the timing of attentional selection could explain the low prevalence of object-based effects. Two different approaches were used to assess the temporal course of attentional selection: bootstrapping to investigate cue-to-target intervals with maximum object-based effects in the time domain and fast Fourier transform to investigate the rhythmic sampling of visual space in the frequency domain.

In the time domain, on the group level, we found large and stable space-based effects in reaction times across all cue-to-target intervals. However, object-based effects were small and appeared mainly at intervals between 100 and 400 ms. On the level of individual participants, most participants exhibited space-based effects in all cue-to-target intervals. In contrast, only a minority of participants showed object-based effects (<20% at each cue-to-target interval), with the highest prevalence at cue-to-target intervals between 210 and 340 ms. In the frequency domain, no rhythmic sampling at 4–10 Hz was found for all the three locations: cued, same-object, and different-object

locations. On the individual level, significant spectral amplitudes were only observed in a small number of participants.

Results in the time domain are in accordance with previous studies that found space-based effects to be much larger and more robust to stimulus manipulations than object-based effects (Avrahami, 1999; Egly et al., 1994; Hecht & Vecera, 2007; Macquistan, 1997; Moore et al., 1998; Pilz et al., 2012). Our findings further support previous research by Pilz et al. (2012), who investigated individual differences in object-based attention and found a low-prevalence of object-based effects across three different paradigms. We extend the findings of Pilz et al. by showing that the timing of object-based effects differs between individuals. That is, individuals differed in the time-point at which object-based effects occurred, with most participants showing object-based effects only at a few time-points. Therefore, using constant cue-to-target intervals, as in Pilz et al., may have only captured object-based effects for a limited number of participants.

It is important to note that we only included horizontal objects rather than randomly selecting from vertical or horizontal object orientations on each trial, given the emphasis on temporal aspects of object-based attention and the overall duration of the experiment. Previous studies have shown that attention spreads more easily along the horizontal compared to the vertical meridian (Barnas & Greenberg, 2016; Hein et al., 2017). Using only horizontal rectangles, we could not clearly differentiate between object-based effects and those relating to an attentional advantage along the horizontal meridian. However, object-based effects have been shown to be either similar for both types of rectangles (Egly et al., 1994; Fiebelkorn et al., 2013; Moore et al., 1998; Nah et al., 2018) or slightly enlarged for horizontal ones (Barnas & Greenberg, 2016; Hein et al., 2017; Pilz et al., 2012). Therefore, the attentional advantage along the horizontal meridian is unable to fully explain object-based effects. In addition, if anything, we would have expected to find stronger object-based effects when using only horizontal rectangles, which is not the case.

In the frequency domain, our findings were inconsistent with studies showing the rhythmic nature of attention (Chakravarthi & VanRullen, 2012; Fiebelkorn & Kastner, 2019; Landau & Fries, 2012;

Vanrullen, 2013). Previous studies observed attention rhythmically samples visual space with 6–8 Hz periodicities (Busch et al., 2009; Dugué et al., 2016; Fiebelkorn et al., 2013; VanRullen et al., 2007) and 3–4 Hz periodicities in the sampling of multiple locations (Fiebelkorn et al., 2013; Landau & Fries, 2012; Re et al., 2019). In a two-rectangle detection task, Fiebelkorn et al. (2013) found that attention rhythmically sampled locations within (8 Hz) and between objects (4 Hz). Their results highlight 8 Hz periodicities for cued and same-object location, suggesting that attention to the cued location spreads along the object to the same-object location periodically.

Several experimental design differences may account for the discrepancy between the results of Fiebelkorn et al. (2013) and ours. First, Fiebelkorn et al. (2013) investigated rhythmicity in attentional sampling based on detection rates (accuracy) of near-threshold targets, whereas we employed a visual discrimination task, which is in line with classical object-based paradigms (Moore et al., 1998; Pilz et al., 2012), and primarily measured reaction times (due to the high accuracy in our study). Reaction time and accuracy have been shown to reveal different attentional mechanisms (Mordkoff & Egeth, 1993; Prinzmetal, McCool, et al., 2005; Prinzmetal, Park, et al., 2005; Santee & Egeth, 1982; van Ede et al., 2012). While RT is thought to reflect both voluntary and involuntary attentional mechanisms, accuracy is thought to reflect only voluntary mechanisms (Prinzmetal, McCool, et al., 2005; Prinzmetal, Park, et al., 2005). Further, RT might be affected by neural oscillations other than attentional ones. For example, RTs could be affected by oscillations in motor regions (Bogacz et al., 2010; Pollok et al., 2015; Van Veen et al., 2008). Second, given high cue validity, it is likely that participants on each trial moved their attention to the cued location, and moved their attention away from the cued location on invalid trials in an object-based manner, first to the same object, and then to the different object: our results show fastest responses for valid trials, but slower responses for invalid-different trials than invalid-same trials. RT differences between invalid-same and invalid-different trials were 35 ms, which corresponds to the typical serial search slope of 20–40 ms/item (Hulleman et al., 2020; Hulleman & Olivers, 2015; Wolfe, 2021). When cue validity is high, there is no strategic advantage for participants to attend to uncued locations (Pilz et al., 2012; Yeari & Goldsmith, 2010).

It is also important to note that contrary to studies showing rhythmicity in attentional sampling, other studies have failed to observe significant periodicities (Brookshire, 2021), or observed periodicities only at uncued locations (Peters et al., 2020; van der Werf et al., 2021). Using alternative analysis (AR surrogate analysis) to examine published data-sets, Brookshire (2021) found that rhythmic temporal structure in attention is not as prevalent as previously assumed, and suggested that behavioral oscillations can be explained by autocorrelation in the time series, rather than attentional periodicity.

In conclusion, the present study supports previous studies in that object-based attention is not as prevalent as previously assumed. Further, our results show large individual differences in temporal aspects of object-based attention, which may explain the low prevalence of object-based effects in previous studies with a fixed cue-to-target interval. Investigating object-based attention based on RTs in a discrimination task, our results do not support the theory that participants reweigh attentional priorities on a moment-to-moment basis (e.g., Fiebelkorn et al., 2013; Helfrich et al., 2018). However, it is likely that object-based effects strongly depend on cue validity. Therefore, the relationship between cue validity and the rhythmic sampling of visual space needs further investigation. Overall, our results provide strong evidence for considering individual variations in developing theories of visual attention.

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Supplemental Information

1. Accuracy

At a level of 0.05, a 51 (cue-to-target interval) x 3 (condition) repeated measures ANOVA showed a significant main effect of conditions ($F(2, 84) = 13.46, p < 0.001, \eta_p^2 = 0.24$). Accuracy was higher for valid trials ($M = 96\%, SD = 0.4$) than accuracy for invalid trials (invalid-same trials: $M = 89\%, SD = 1.3$; invalid-different trials: $M = 90\%, SD = 1.1$). The main effect of cue-to-target interval ($F(50, 2100) = 1.59, p = 0.14, \eta_p^2 = 0.04$) and the interaction ($F(100, 4200) = 1.46, p = 0.13, \eta_p^2 = 0.03$) were not significant, indicating that the accuracy did not change across cue-to-target intervals. T-tests results (FDR corrected) showed significant space-based effects across all cue-to-target intervals, whereas no significant object-based effects were found for any cue-to-target intervals (Supplemental Figure S1).

Figure S1. a) Average accuracy (mean±1 SEM) for valid trials (blue), invalid-same trials (yellow) and invalid-different trials (red) for all cue-to-target intervals. b) Space- (green) and object-based effects (orange) in accuracy for all cue-to-target intervals. Filled dots showed cue-to-target intervals with significant effects from t-tests results.

2. Space- and object-based effects for individual participants

Figure S2. Examples of different patterns of space- and object-based effects across cue-to-target intervals for a selection of individual participants. The red dots showed cue-to-target intervals with significant effects.

3. Bayesian statistics for null hypothesis

To provide an unbiased criterion with regards to the null hypothesis, we applied Bayesian statistics on the accuracy data with JASP (Wagenmakers, Love, et al., 2018; Wagenmakers, Marsman, et al., 2018). Two fitted models, one with Cue-to-target interval and with the interaction between Cue-to-target interval and Condition, were compared separately with the null model. The results with a Bayes Factor $BF_{10} < 1/10$ provide strong evidence in favor of the null hypothesis (Lee & Wagenmakers, 2013; Wagenmakers, Love, et al., 2018) for both the main effect of cue-to-target interval ($BF_{10} = 9.57 \times 10^{-10}$) and the cue-to-target interval x condition interaction ($BF_{10} = 1.7 \times 10^{-9}$).

4. Bootstrapped results with subsampled dataset

One concern is the unbalanced power to detect space- and object-based effects because of the far more valid trials than invalid trials in the current study. To assess whether the number of trials affects the results, we first subsampled the number of valid trials to the equal number of invalid trials. We then followed the same steps as before to investigate individual differences of space- and object-based effects. Figure S3a and S3b showed bootstrapped space- and object-based effects for each participant and each cue-to-target interval for the subsampled data. Black dots showed cue-to-target intervals with significant effects. White dots in Figure S3b showed cue-to-target intervals with significant reversed object-based effects (different-object advantage). Figure S3c showed the percentage of participants with significant space-, object- and reversed object-based effects for each

cue-to-target interval.

As shown in the figures, bootstrapped space-based effects (Figure S3a) were far more prevalent than object-based effects (Figure S3b). On average, 68.5% of participants showed space-based effects, whereas 10.6% of participants showed significant object-based effects and 2.1% of participants showed negative object-based effects. These results suggest that subsampling the number of valid trials did not affect the observed pattern of space- and object-based effects to a great extent.

Figure S3. a) Bootstrapped space-based effects in reaction time for individual participants for each cue-to-target interval. b) Bootstrapped object-based effects in reaction time for individual participants for each cue-to-target interval. Black dots indicate cue-to-target intervals with significant bootstrapped effects. White dots showed cue-to-target intervals with significant reversed object-based effects (different-object advantage). c) The percentage of participants with significant space- (green bar), object- (orange bar), and reversed object-based effects (white bars) in reaction times for each cue-to-target interval. Average percentage of space- (68.5%) and object- (10.6%) and reversed object-based effects (2.1%) were indicated by green/black line, orange/black line and white/black line respectively.