Completeness of Filling-Up in the Filled/Unfilled Illusion

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Introduction. The results of a number of studies of the filled/unfilled illusion demonstrated an overestimation of the filled part of the stimulus in comparison with the unfilled one of the same length. Despite the fact that the illusion is rather well studied experimentally, its origin is not yet sufficiently understood. It was demonstrated [1, 2] that uniformity and regular distribution of the filling elements is important for the illusion manifestation, and that a certain number (7 – 15) of equidistantly placed filling elements evokes an illusion of maximum strength. Therefore, stimuli with regularly distributed fillers received more attention from researchers, and questions concerning the illusion parameters in the case of continuous filling-up still remain open.

In order to clarify the issue, in the present pilot study, we examined the illusory effect as a function of the length of the contextual line segment (shaft) filling the referential part of the horizontal three-dot stimulus. It was expected that the magnitude of the illusion should in a regular way depend on the completeness of filling-up, thus providing additional information, which can be helpful for further development of a quantitative description of phenomenon of the filled/unfilled illusion.

Stimuli and procedure. The stimuli used in the experiments comprised three dots arranged horizontally, which were considered as terminators specifying the left (*L,* referential) and right (*R,* test) spatial intervals (Fig. 1). Contextual horizontal line segment (shaft) was centered in the referential interval of the stimulus. Size of the dots and the thickness of the shaft was 1 *min arc*; stimulus luminance, 75 cd/m^2.

In the first series of experiments, the length of the referential interval was fixed at 60 *min arc*, and the shaft length, *d* (the independent variable) altered from 0 to 60 *min arc* in a random fashion. In the second series, the length of the shaft was set to 45 *min arc*, and the length of the referential interval, *L* varied in a range from 45 to 90 *min arc*. Subjects were asked to move the lateral terminator of the test interval into a position that makes both stimulus intervals perceptually equal in length. The physical difference of lengths, $R – L$, was considered as the value of the illusion magnitude. The initial length differences between the left and right stimulus intervals were randomized and distributed evenly within a range of ±10 *min arc*.

The experiments were carried out in a dark room (the surrounding illumination < 0.2 *cd/m*^{2}). The stimuli were presented in the center of a Sony *SDM-HS95P* monitor (against a dark round-shaped background 5° in diameter and 0.4 *cd/m*^{2} in luminance) calibrated and gamma corrected by a Cambridge Research Systems *OptiCAL* photometer. A chin rest, and forehead support were provided to limit the head movements. The 3 *mm* diameter artificial pupil was used to minimize the optical aberrations; the distance between the subject's eye and the screen was 330 *cm*. The subjects' eyes movements were not registered and observation time was not limited.

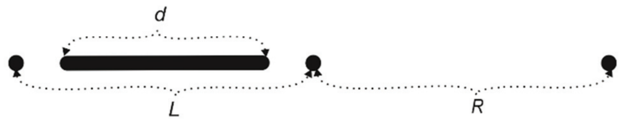

Fig. 1. Example of a stimulus used in the experiments. *L* and *R*, the referential and test intervals, respectively; *d*, the length of contextual line segment. *Dotted* lines, the dimensions were not part of the actual display

An experimental run comprised 40 stimulus presentations, i.e., 20 different values of the independent variable were taken at random twice. Ten trials went into each data point analysis. In the data graphs, the error bars depict ± one standard error of the mean (SEM).

Six subjects (4 female and 2 male; 19-21 years old) participated in the study, each carrying out at least ten experimental runs on different days. The subjects gave their informed consent before taking part in the experiments, which were performed in accordance with the ethical standards of the 1964 Helsinki Declaration.

Results and discussion. The results of the first series of experiments are shown in Fig. 2 (*upper*, *left* graph). It can be seen that for all subjects the data collected showed a non-linear functional dependence of the illusion magnitude on the completeness of filling. The magnitude of the illusion changes rather little with increasing shaft length up to about 40 *min arc*. Further shaft lengthening leads to a rapid increase of the illusion magnitude, which gains its maximum value (about 10 *min arc*) in the case of completely filled referential interval of the stimulus.

In the second series of experiments, the shaft length was constant (45 *min arc*), whereas the length of the referential interval randomly varied in a range from 45 to 90 *min arc*. According to the data obtained from six subjects (Fig. 2 *lower, left* graph), the illusion strength decreases gradually (from about 5 to about 1 *min arc*; the data slightly differ for different subjects) when the interval length increases.

The dependencies established in the first and second series of experiments were used to develop a semi-empirical mathematical model. In the model, we supposed that the illusion magnitude non-linearly depends on the ratio of lengths of the contextual line, *d* and referential interval, *L* (i.e., on the completeness of filling of the interval). We also suggested the procedure of a weighted spatial integration of the neural excitation within a certain attentional window (linearly increasing in size with retinal eccentricity) described earlier to account effects of automatic centroid extraction [3].

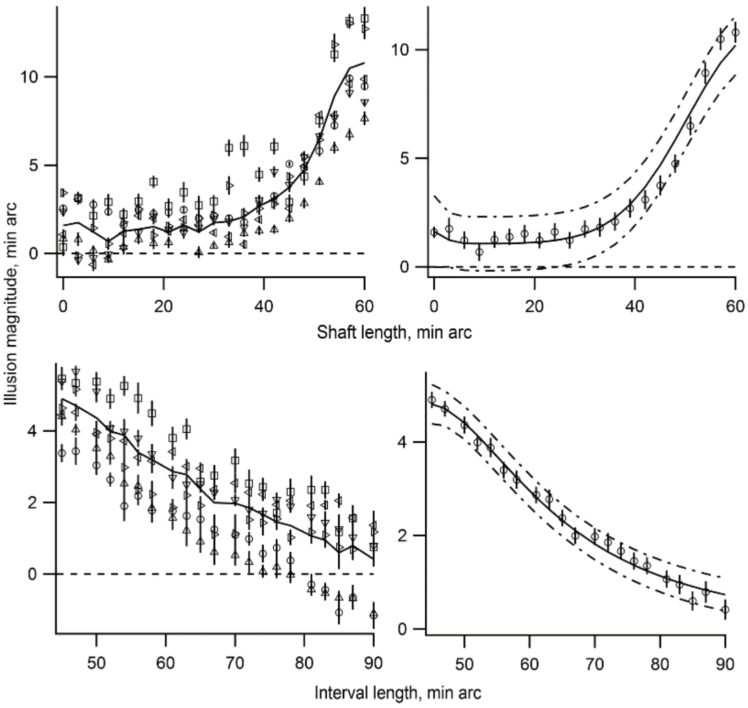

Fig. 2. Magnitude of the filled/unfilled illusion as the functions of the shaft length (*upper* row) and referential interval length (*lower* row). *Left* column: *solid* curve, averaged data for all observers. *Right* column: *solid* curve, least squares fitting by the model function; *dash-dot* curves, confidence intervals of the fitting. *Vertical* bars, ± one SEM

As a result, it was established that a rather good assessment of the effect of filling-up of the referential stimulus interval can be obtained using the following approximate formula:

$$I(d,L) \cong kL\left(\frac{d}{L}\right)^2 e^{-\frac{1}{2}\left(\frac{L-d}{\mu L}\right)^2} \quad (1)$$

where L and d refer to the lengths of the referential interval and the shaft, respectively; k is coefficient of proportionality; μ is a scale factor ($\sigma = \mu L$, where σ represents the standard deviation of the Gaussian profile of attentional window).

To test the model, we fitted (method of least squares) the experimental data presented in Fig. 2 (*left* column, *solid* curves) with the function (1). Two free parameters (coefficients k and μ) were used for fitting. A good resemblance between the computational and experimental results was obtained (Fig. 2, *right* column, *solid* curves); the value of coefficient of determination R^2 was higher than 0.9. A more careful examination of the goodness-of-fit by statistical analysis of the data with the Shapiro-Wilk test (assessment of normality of residuals) has also confirmed the validity of our model. The values of k (0.13±0.017) and σ (5.92±3.4 *min arc*) obtained in the model approximations are rather consistent with our previous findings in experiments with the Oppel-Kundt [1] and Müller-Lyer figures [3].

Conclusion. It was demonstrated that the filling-up of the referential stimulus interval by the contextual line segment in a regular way changes the magnitude of the filled/unfilled illusion. A good resemblance between the computational and experimental results confirms our previous findings and supports the suggestion regarding the processes of a certain weighted integration of spatial information.

References

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The present study is concerned with a contextual filling-up inducing the illusion of extent. The results of the psychophysical experiments showed a non-linear functional dependence of the illusion magnitude on the completeness of filling. The data collected were used to verify the predictions of our semi-empirical computational model, and it was demonstrated that the model calculations adequately account for the illusion magnitude variations shown by all the subjects tested.