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A MATHEMATICAL ANALYSIS OF THE CONVENIENT VIEWING POSITION HYPOTHESIS AND ITS COMPONENTS

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Introduction

The raw data of a convenient viewing position (CVP) experiment are difficult to analyze. The variable "first letter fixated" has a different number of levels depending on word length. It may also show unequal intervals between the levels (e.g. in our experiments every letter of a short word is presented on the fixation location whereas for long words this is only true for the odd letters). This makes statistical analyses cumbersome and sometimes impossible. Moreover, due to the multitude of levels involved in the "first letter fixated"- variable, interactions between this variable and other manipulations are not easy to interpret. Therefore, it would be interesting if the pattern of responses could be split up into a limited number of (meaningful) components that are comparable across conditions and experiments. We shall first develop a model on the basis of data from Brysbaert and d'Ydewalle (1988), and then apply it to two new experiments in order to see whether the parameters of the former experiment are extendable.

Development of the model

The CVP concerns faster processing of words if the eyes initially fixate between the beginning and the middle of a word (O'Regan & Lévy-Schoen, 1987; Brysbaert & d'Ydewalle, 1988; Vitu & O'Regan, 1988; Osaka, 1990). Three major factors are thought to underly this phenomenon: sensory constraints (O'Regan & Lévy-Schoen, 1987), lexical constraints (O'Regan & Lévy-Schoen, 1987) and callosal transmission time (Brysbaert & d'Ydewalle, 1988). Sensory constraints refer to the drop of visual acuity outside the fovea and explain why gaze durations are longer when fixations are situated at the very beginning or end of a word. If these constraints were the sole factor of importance, the CVP would lie in the middle of a word and response times would vary as a U-shaped function according to the letter initially fixated. Lexical constraints point to the fact that in Western languages words are processed from left to right and that the first part of a word is usually the most informative part. Callosal transmission, finally, refers to the need for interhemispheric transfer if part of a word falls in the left visual field. This is because most people (about 95%) have their linguistic capacities primarily situated in the left cerebral hemisphere and the left visual field does not have direct connections to that half of the brain. Both lexical constraints and callosal transmission predict an increase in response time if words are fixated more towards the end, and together with the sensory constraints account for the J-shaped curve usually encountered in CVP experiments.

Assuming that these three factors actually exist, the above analysis suggests that the pattern of results in a CVP experiment can be described mathematically as the sum of three components. First, there is the quadratic (U-shaped) component referring to the sensory constraints. Second, there is a linear component caused by the lexical constraints of the stimuli and the cerebral asymmetry of the subject. And third, there is a time factor related to the processing of a word when the influence of the other two components is minimal (the constant or **a** component). In our model the last component will be the processing time when the word is initially fixated in the middle. It coincides more or less with reaction times obtained from word processing experiments in which the "first letter fixated" is not manipulated. The simplest equation that incorporates all three components is a polynomial of the second degree, i.e.

$$RL = a + b(l - m) + c(l - m)^2 \tag{1}$$

in which RL = the reaction latency, l = rank number of the letter fixated, m = middle of the word (equals 2 for a 3-letter word, and 2.5 for a 4-letter word).

Eq. (1) is preferred over the alternative and mathematically equivalent equation $\mathbf{RL = a + b*l + c*l^2}$ for two reasons: first, the quadratic component agrees more with the process it attempts to simulate (faster responses when the middle letter is fixated and slower responses when letters towards the extremes are fixated), and second, the three components in Eq. (1) are largely independent of each other which is not true for the alternative equation. This has the advantage that the value of **b** does not change if the exponent of the quadratic term is modified (see below, the **a** value changes slightly if the quadratic term is altered). Eq. (1) is also preferred over the alternative equation proposed by McConkie et al. (1989) $\mathbf{RL = a + b(l - c)^2}$ in which the J shape of the curve is captured by introducing a parameter **c** that stands for the letter position in the word where the curve reaches its lowest point. The lowest point of the curve is believed to be the result of more basic processes (see above) and not an essential characteristic of either the stimulus or the subject. Therefore, there is no need to introduce it as a separate parameter into the model.

To get an estimate of the **a-**, **b-**, and **c**-components, Eq. (1) was applied to Brysbaert and d'Ydewalle (1988). In their experiment the CVP was examined for 3-, 4-, 5-, 7-, and 9-letter words. Subjects fixated a gap between two vertical lines placed just above and below the position where the test word was to appear. Lower case words were presented in such a way that a different letter position lay between the fixation lines. For the 3-, the 4-, and the 5-letter words every letter had to be fixated; for the 7- and the 9-letter words this was only true for the odd letters. Subjects were asked to name the words as rapidly and accurately as possible. Other independent variables apart from word length were cerebral asymmetry (between-subjects) and viewing condition (binocularly, monocularly with the left eye, and monocularly with the right eye; within-subjects variable). All subjects finished a number of latin-square designs in each condition (the stimulus series of 482 words was repeated 30 times for each subject), so that the parameters of Eq. (1) could be estimated for each subject separately. Below, the average per word length is given. Numbers between brackets indicate the mean percentage of variance the model accounted for per subject.

(i)	3-letter words:	$RL = 446 + 2.7\ (l\text{-}m) + 3.9\ (l\text{-}m)^2$	(100%),
(ii)	4-letter words:	$RL = 454 + 3.1\ (l\text{-}m) + 2.4\ (l\text{-}m)^2$	(87%),
(iii)	5-letter words:	$RL = 458 + 3.3\ (l\text{-}m) + 1.8\ (l\text{-}m)^2$	(86%),
(iv)	7-letter words:	$RL = 469 + 4.4\ (l\text{-}m) + 1.4\ (l\text{-}m)^2$	(98%),
(v)	9-letter words:	$RL = 474 + 5.1\ (l\text{-}m) + 1.1\ (l\text{-}m)^2$	(95%).

Analysis of variance showed that word length had a significant effect on each of the three components: the time-constant and the weight of the linear component augmented as word-length increased, whereas the weight of the quadratic component decreased. No other main effect (cerebral asymmetry or eye used) or interaction effect was significant for any of the three components. The absence of a significant main effect ($p = 0.11$) of cerebral asymmetry on the linear component (which is the core of the Brysbaert and d'Ydewalle, 1988 article) is due to the small number of subjects used in the experiment (three subjects with left cerebral dominance and two with right cerebral dominance). The multiple correlation between the laterality indices and the weight of the linear component was 0.76 ($n = 5$).

Whereas the increase of the constant and the weight of the linear component due to the increase of word-length are not surprising, it was not expected that the weight of the quadratic component would decrease as the words grew longer. This would imply that the effect of the drop of visual acuity outside the fixation position is smaller for long words than for short words. A possible explanation might be that the exponent of the quadratic component is too high and therefore the curvature of the function too sharp (e.g. a letter four positions away from the middle gets a value of 16). To find out whether the value of the exponent had indeed caused the word-length effect, an iterative procedure investigated whether there was a value of the exponent that eliminated the decrease of the weight. That optimal value did indeed exist and was situated around 1.24 (with **c** values of 3.93, 3.96, 3.14, 3.88, and 3.37 for the 3-, the 4-, the 5-, the 7-, and the 9-letter words respectively). Analysis of other data (see below), however, gave best values ranging between 1.60 and 1.86. In all cases, an exponent of 1.5 was satisfactory because it led to the absence of a significant relationship ($p > 0.20$) between word-length and the weight of the quadratic component. As long as there is no independent evidence that the drop of visual acuity exhibits irregularities across the visual field, we think it is reasonable to assume that the cost in time dependent on the distance from the fixation position is best characterized by a smooth parabola with exponent 1.5 and a constant weight. Therefore Eq. (1) is better replaced by the following equation:

$$RL = a + b(l - m) + c|l - m|^{1.5} \qquad (2)$$

in which $|l - m|$ = the absolute value of l-m.

The mean values of the constant **a** in Eq. (2) are the same as in Eq. (1) give or take one millisecond. As indicated above, the **b** values also remain the same, as do the mean percentages of explained variance. Mean weight of the quadratic component is 3.01.

Testing the model

The model should meet two requirements: first, parameters must remain stable over replications, and second, the model must not disregard important aspects of the CVP data.

In order to check the first requirement, stability over replications, parameters obtained in comparable experimental conditions from three independent studies were compared. In all conditions, subjects were males with left cerebral dominance, viewing was binocular, the dependent variable was naming latency and the stimuli were 5- and 9-letter words. Considerable differences, however, were also present. Most notable among them were (i) that the stimuli remained on the screen until the subject reacted in experiments 1 and 3, whereas they were replaced by a mask after 180 ms in experiment 2, (ii) that the degree of lateralization was controlled explicitly in experiment 1 and 2, whereas in experiment 3 subjects only had to be righthanded, (iii) that the crucial conditions were embedded in varying numbers of other within-subject conditions and hence in varying numbers of stimulus repetitions, and (iv) that the subjects of the first two studies were undergraduate students, whereas the subjects of the last study were research assistants. The first study was the experiment of Brysbaert and d'Ydewalle (1988), already mentioned above. The second study consisted of two parts: one in which the subjects had to read the words aloud (naming), and one in which the subjects had to decide whether the stimulus was a word or not (lexical decision). Non-words were formed by changing a random letter of the words. The first part (which is the essential one for this section) was a replication of the Brysbaert and d'Ydewalle (1988) experiment, except for stimulus duration which was limited to 180 ms. An abstract of the study can be found in Brysbaert and d'Ydewalle (1989). The third and last study compared performance under optimal viewing conditions with performance under reduced viewing conditions (varied by manipulating the strength of the glasses the subjects wore, see also below). Task characteristics were the same as for the first study, except that only 5- and 9-letter words were presented. The number of subjects in the critical conditions were three, five, and five respectively.

The results of the three studies are:

Experiment 1 (Brysbaert & d'Ydewalle, 1988)

5-letter words :	$480 + 3.8\ (l\text{-}m) + 1.6\ [l\text{-}m]^{1.5}$	(91%),
9-letter words :	$494 + 5.2\ (l\text{-}m) + 2.3\ [l\text{-}m]^{1.5}$	(98%),

Experiment 2 (Brysbaert & d'Ydewalle, 1989)

5-letter words :	$440 + 2.6\ (l\text{-}m) + 2.9\ [l\text{-}m]^{1.5}$	(87%),
9-letter words :	$455 + 7.0\ (l\text{-}m) + 3.8\ [l\text{-}m]^{1.5}$	(96%),

Experiment 3 (Brysbaert & d'Ydewalle, in preparation)

5-letter words :	$447 + 1.7\ (l\text{-}m) + 3.2\ [l\text{-}m]^{1.5}$	(82%),
9-letter words :	$462 + 5.7\ (l\text{-}m) + 3.0\ [l\text{-}m]^{1.5}$	(96%).

Though there are some variations in the data, analysis of variance showed no significant difference between the three studies for any of the parameters (p-values for main and interaction effects involving the variable "Study" all were larger than 0.15). Thus, the parameters of the model seem to be stable enough to allow comparisons across experiments.

The second requirement which the model has to meet is that it should not exclude important aspects of the data. Although the percentages of variance accounted for are quite high (80% and more, see above), it still might be the case that part of the variance not accounted for is due to a systematic deviation from the model. A (simple) way to check this is to compare the averages of the parameters obtained from each individual subject with the parameters calculated on the mean data. If the variance not accounted for is random noise, then both estimates of the parameters should be identical and for the mean data percentage of explained variance should approximate 100% [note that this requirement is always met for the 3-letter words, because three data points are fully described by a polynomial of the second degree]. Below, the data are given for the optimal viewing conditions (optimal strength of the glasses) of the third experiment only, although the model has been tested with success for all conditions of the three experiments. The data are based on 10 subjects (five males, see above, and five females):

- 5-l :	av. parameter:	$435 + 2.3\ (l\text{-}m) + 3.4\ [l\text{-}m]^{1.5}$	(84%),
	model mean data:	$435 + 2.3\ (l\text{-}m) + 3.3\ [l\text{-}m]^{1.5}$	(100%),
- 9-l :	av. parameter:	$452 + 6.4\ (l\text{-}m) + 3.3\ [l\text{-}m]^{1.5}$	(96%),
	model mean data:	$452 + 6.4\ (l\text{-}m) + 3.3\ [l\text{-}m]^{1.5}$	(99%).

Because both requirements are met, the model described in Eq. (2) can be used to describe the data pattern of a CVP experiment without loss of information. The advantages of the model are (i) that the patterns of all word-lengths are translated in three comparable parameters, and (ii) that the parameters correspond to basic processes that are thought to underlie the reaction latencies in a CVP experiment.

Some applications of the model

Callosal transmission

Brysbaert and d'Ydewalle (1988) hypothesized that initial fixations at the beginning of a word would be more advantageous for most people than fixations at the end of a word because in the latter case the largest part of the word lies in the left visual field which does not communicate directly with the dominant left cerebral hemisphere. Only for the few people (about 5% of the population) with language in the right cerebral hemisphere would this advantage be smaller (the advantage would probably not completely disappear because of the lexical constraints discussed above, see also O'Regan and Lévy-Schoen, 1987). Reanalysis of the Brysbaert and d'Ydewalle (1988) data with the use of the above model indicates that there is indeed a strong correlation ($r = 0.76$, see above) between the laterality indices and the linear component of the model, but that due to the small number of subjects used (five), this correlation fails to reach significance. In a further experiment (Brysbaert & d'Ydewalle, 1989, see also above, experiment 2), in which 10 subjects were studied (five left cerebral dominant, three bilateral, and two right cerebral dominant), the difference in the linear component between the left cerebral and the not-left cerebral dominant group was significant ($p < 0.05$), but tended to be larger for lexical decision than for naming (interaction cerebral dominance and task, $p = 0.08$). Cerebral dominance did not have an effect on any of the other parameters (**a**, **c**, or percentage explained variance; all F-values were smaller than 1). Efforts are currently being made to find more bilateral and right cerebral dominant subjects in order to improve the generalizability of the results.

Naming versus lexical decision

In experiment 2, we also compared the performance of subjects on a naming and a lexical decision task. Subjects first finished 15 series of 482 3-, 4-, 5-, 7-, and 9-letter words which had to be named and then started another 15 series with 3-, 4-, 5-, 7-, and 9-letter stimuli, half of which were words and half non-words. Non-words were made by changing a random letter of the words.

Analysis of variance on the **a** values indicated that lexical decision took significantly longer than naming ($p < 0.05$), but unequally so for different word lengths ($p < 0.001$ for the interaction word-length * task). Response time increased linearly with word-length in the naming task (**a** values of 434, 440, 439, 450, and 452 for the 3-, the 4-, the 5-, the 7-, and the 9-letter words respectively), but not in the lexical decision task (**a** values of 497, 487, 468, 468, 480 respectively). Thus the major differences between naming and lexical decision occur at the level of short words.

Analysis of variance on the **b** values indicated no main effect of task (mean value of 2.9 for naming and 4.2 for lexical decision), but an almost significant interaction between task and cerebral dominance (see above). The difference between left cerebral dominant subjects and not-left cerebral dominant subjects was larger for lexical decision than for the naming task.

Finally, the **c** values were significantly larger in the lexical decision task (c = 7.49) than in the naming task (c = 2.65). No differences were found in percentage of explained variance.

Overall, the picture agrees reasonably well with previous findings. Lexical decision is known to take longer than simple naming (Balota & Chumbley, 1984, table captions 3 and 4), so an increase in the **a** parameter was to be expected. Similarly, callosal transmission time is assumed to be a function of the amount of information that has to be transmitted (Brysbaert & d'Ydewalle, 1988), and thus should increase if the task is more demanding. Finally, it is not unreasonable to assume that visual acuity plays a larger role in a lexical decision task where each random letter can be replaced than in a simple naming task where (pronunciation) constraints limit the number of possible letter strings. Only the interaction between task and word length on the constant is new. Further experiments are needed to check whether this results from different access to the lexicon or is due to production processes (Balota & Chumbley, 1985).

Visual acuity

In a recent experiment, Brysbaert and d'Ydewalle (in preparation, see also above, experiment 3) compared the CVP pattern of naming latency for myopic subjects when they read with their normal glasses and with lenses that were one diopter too weak. It was expected that the weakness of the lenses would lead to an increase in the constant (the **a** value) and the quadratic component (the **c** value). The stimuli were 200 5-letter and 200 9-letter words. Ten subjects received 11 presentations of all stimuli: one practice series and five series with correct and weak lenses each (presented in an abba order). Viewing time was unrestricted. Half of the subjects were male, half female. Results for the different conditions are presented below.

normal lenses :	5-l :	$435 + 2.3\ (l\text{-}m) + 3.4\ [l\text{-}m]^{1.5}$	(84%),
	9-l :	$452 + 6.4\ (l\text{-}m) + 3.3\ [l\text{-}m]^{1.5}$	(96%),
weak lenses :	5-l :	$440 + 3.3\ (l\text{-}m) + 3.2\ [l\text{-}m]^{1.5}$	(84%),
	9-l :	$455 + 7.2\ (l\text{-}m) + 3.6\ [l\text{-}m]^{1.5}$	(97%),

Contrary to expectations, reducing the effectiveness of the lenses did not have a significant effect on the constant ($p = 0.12$) or the quadratic component ($p > 0.500$), but significantly influenced the linear parameter ($p < 0.05$). That is, the effect of the lenses was completely absent when the subject's first fixation was at the beginning of the word and became gradually more substantial (though still rather small) as the subject's first fixation fell more towards the end of the word. It was not possible to check whether this result was due to lexical constraints or to interhemispheric transmission because only left cerebral dominant subjects were investigated. Nor did the experiment provide an answer to the question as to whether the good results in the "weak lenses" condition were obtained at the expense of greater effort on the part of the subjects.

Experience

Because the stimulus series was repeated a number of times in our experiments, it is possible to check the influence of experience on the different parameters. For the sake of clarity, we will confine the discussion to a comparison of the 5- and 9-letter words of the first and eleventh series of experiment 2 described above. The comparison is made only for naming because the stimuli in the lexical decision condition had already been presented 15 times previously (i.e. the naming conditions). The first and the eleventh series are compared because they contain the same stimuli per subject and condition (the design was a latin square repeated three times per subject). The results were:

5-letter:	series 1 :	$472 + 2.2\,(l\text{-}m) + 3.7\,[l\text{-}m]^{1.5}$	(64%),
	series 11 :	$420 + 1.9\,(l\text{-}m) + 3.7\,[l\text{-}m]^{1.5}$	(77%),
9-letter:	series 1 :	$490 + 9.8\,(l\text{-}m) + 6.1\,[l\text{-}m]^{1.5}$	(99%),
	series 11 :	$429 + 4.8\,(l\text{-}m) + 4.3\,[l\text{-}m]^{1.5}$	(97%).

Experience had a clear effect on the constant of both word-lengths and on the linear component of the 9-letter words. The quadratic component remained quite stable (at least in this experiment where subjects had already finished eight hours of related experiments to determine their lateralization). Because the linear component is assumed to be the result of two factors (lexical constraints and interhemispheric transmission), it might be interesting to investigate whether the drop from 9.8 to 4.8 in the 9-letter words was mainly due to one or the other factor, or to both. The results below show that the last alternative is the most probable one. The decrease for the left dominant subjects was more considerable than that for the not-left cerebral dominant subjects, though the drop was clearly present in both groups. Unfortunately, because we did not have a complete latin square design per subject, it is not possible to calculate the model for each subject so as to be able to run an ANOVA to check the significance of the differences.

9-letter words:

series 1 :	left dominant:	$493 + 12.8\,(l\text{-}m) + 6.6\,[l\text{-}m]^{1.5}$	(97%),
	n-left dominant:	$488 + 6.7\,(l\text{-}m) + 5.4\,[l\text{-}m]^{1.5}$	(97%),
series 11 :	left dominant:	$431 + 5.8\,(l\text{-}m) + 5.4\,[l\text{-}m]^{1.5}$	(97%),
	n-left dominant:	$426 + 3.6\,(l\text{-}m) + 3.3\,[l\text{-}m]^{1.5}$	(96%).

Conclusion

We have argued that the pattern of data obtained in a CVP experiment can be described by a (modified) polynomial of the second degree (see Eq. (2)). The three components of the polynomial are thought to correspond to distinct psychological processes. The constant refers to processes unrelated to CVP manipulations and roughly coincides with reaction times obtained after initial fixation in the middle of the word. The linear component refers to the combined effect of lexical constraints (left-to-right processing of words and more information in the first part of a word) and callosal transmission time (usually more transmission if fixations toward the end of a word). Finally, the quadratic component is assumed to correspond to the drop of visual acuity outside the fovea and did indeed remain unaffected by manipulations that were unrelated to visual acuity (although it also remained unaffected by a manipulation that was thought to increase the role of visual acuity).

The model accounts for most of the systematic variation in CVP patterns and comparison of similar conditions in three unrelated experiments shows that the parameters of the model remain fairly stable. Thus, results across different experiments can be compared. If a model is obtained for each subject, statistical analyses are easy to perform.

Various applications of the model are outlined towards the end of the article. It is shown, as was predicted, that interhemispheric transmission influences only the linear component, that naming and lexical decision tasks differ from one another in all three components, that diminishing the visual acuity of the subjects by one diopter affects only the linear component and not, as was predicted, the quadratic component, and that the effect of experience is mainly situated in the constant and to a lesser extent in the linear component. Other applications are possible, the most interesting of which might be to calculate the model for a number of words and to investigate how the parameters relate to different properties of those words, such as length, frequency, familiarity, information distribution across the letters, and so on. The parameters for words can be calculated as soon as comparable groups of subjects process the stimuli in a latin square design.

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