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TOWARDS A FORMAL THEORY OF A DISTRACTOR IN ATTENTIONAL TASKS

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TOWARDS A FORMAL THEORY OF A DISTRACTOR IN ATTENTIONAL TASKS[2]

The distractive effects on attentional task performance in different paradigms are analyzed in this paper. I demonstrate how distractors may negatively affect (interference effect), positively (redundancy effect) or neutrally (null effect). Distractor effects described in literature are classified in accordance with their hypothetical source. The general rule of the theory is also introduced. It contains the formal prediction of the particular distractor effect, based on entropy and redundancy measures from the mathematical theory of communication (Shannon, 1948). Single- vs dual-process frameworks are considered for hypothetical mechanisms which underpin the distractor effects. Distractor profiles (DPs) are also introduced for the formalization and simple visualization of experimental data concerning the distractor effects. Typical shapes of DPs and their interpretations are discussed with examples from three frequently cited experiments. Finally, the paper introduces hierarchical hypothesis that states the level-fashion modulating interrelations between distractor effects of different classes.

Keywords: attention, distractor, interference effect, redundancy effect, distractor profile (DP)

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1. **Introduction**

Many classical and contemporary theories of attention and perception emphasize attentional selectivity. Selectivity traditionally has two aspects. On the one hand, selectivity implies the choice of a target or action among others, target highlighting, outstanding significance for consciousness and control of action. On the other hand, selectivity implies the ability to resist the invasion of other stimuli and actions in their attempts to 'possess' perception and action. The critical role of attention in overcoming intrusion and distraction is emphasized by both classical theories (e.g., James, 1890) and contemporary influential models that attribute executive and self-regulation functions to attention (e.g., Rueda et al., 2004; Posner & Fan, 2008).

There are many psychological paradigms investigating the selective aspect of attention. Many of them, such as the Stroop test, flanker task, visual search etc, explicitly induce the competition between task-relevant and task-irrelevant stimulation. I shall term task-relevant and task-irrelevant stimulations as targets and distractors accordingly. In other terms, they may be labeled as attended and ignored stimuli. Both distinctions are quite traditional for the psychology of attention. It is notable that targets and distractors may be defined both as specified items or objects (like items in a visual search) and as particular dimensions or features of these items (like colors and words in the Stroop task).

Although many paradigms deal with the target-distractor dichotomy, all of them are aimed at special issues associated with operations of perception, attention, learning, etc, and therefore rarely discussed together. Moreover, there are a number of paradigms where distractors typically occur, along with implicit targets such as maskers, primes and attentional cues. This paper is an attempt to compare different paradigms, and to reveal and describe the general rules controlling interactions between targets and distractors irrespective of methodology. The model proposed here is a formal one, because it describes the general scheme of target-distractor relations without the essential analysis of causes and consequences, which may differ in any specific case. In the last few decades, the formalization of numerous perceptual paradigms on the grounds of signal detection theory (Logan, 2004; Swets, 1984), economic theory (Kinchla, 1992; Navon & Gopher, 1979; Sperling, 1984), and cost-benefit analysis (Posner, 1978; Posner & Snyder, 1975) has yielded significant progress in the field, by providing relatively simple criteria of attentional processing as well as measurement and prediction opportunities.

2. Typical distractor effects

The most typical and expected distractor effect is the *interference effect*, referred to as decrement in target-related performance when the distractor is concurrently presented. In a narrower sense, a distractor is what typically causes the interference effect. Under standard experimental conditions, interference may manifest itself as increment in sensory thresholds and error rates, or as the inhibition of responses to targets. Typical examples of interference effects are the inhibition of ink color naming in the word-color conflict condition of the Stroop task, the decrement of performance in the presence of acoustic noise and the inhibition of visual search in the presence of irrelevant singleton, known as attentional capture.

However, other distractor effects have also been obtained in numerous studies, along with interference effects. I shall use the word-combination “redundancy effect” to express such effects. In a technical sense, redundancy was introduced by Shannon (1948) in the context of his mathematical theory of communication. According to Shannon’s terminology, redundancy (R) denoted a measure of organization in the information system (message). Redundancy is complementary to relative entropy (E), which serves as the measure of information uncertainty. Redundancy may be considered as the amount of information that may be omitted in the course of message transmission, without a loss in receiving quality. Garner widely applied this redundancy to human perception and attention. He interpreted redundancy as the interaction between relevant and irrelevant signals (modalities, objects, dimensions), which may potentially improve the processing of target stimuli. One term introduced by Garner was ‘redundancy gain’, the facilitation of discrimination performance when a target dimension is highly correlated with the distracting dimension. Another traditional term concerning redundancy is the ‘redundant signal effect’, which describes a situation when the multiplication of a target in stimulus display (both in intramodal and in crossmodal conditions) yields an acceleration of the response to the target despite the irrelevant character of non-target stimuli. As soon as traditional terms such as ‘redundancy gain’ or ‘redundant target effect’ are closely associated with particular paradigms, I prefer to use the broader term *‘redundancy effect’* (Utochkin, 2009) to label the of positive distractor effects. As will be demonstrated further, redundancy effects are rather typical for a wide range of tasks containing distractors of any kind.

Finally, the third possible distractor effect on performance is the *null effect*, when task performance with a distractor does not differ from the one without a distractor. It may be typically considered as evidence that the distractor is successfully ignored. On the other hand, the *“null effect”* may be considered as evidence of a high degree of automaticity of task performance when target stimulus requires little or no attention (Posner & Snyder, 1975).

The «Interference-Redundancy» dimension, including the null effect as an intermediate point will be considered as the unitary basis for the formal theory of the distractor developed in this article.

3. Evidence for the ‘Interference-Redundancy’ dichotomy from various tasks

This section concerns distinct perceptual and attentional paradigms with a distraction of any kind. The tasks and distractor effects will be considered in terms of the ‘Interference-Redundancy’ dimension introduced above. Moreover, these effects may be divided into three classes depending on their presumed source.

3.1. Sensory input effects

Distractor effects of this kind may originate from the co-activation of sensory inputs which correspond to both targets and distractors. Combinations of activation processes depending on specific conditions may both suppress normal target processing (and, hence, interfere with it), or enhance it (with redundancy effects as a consequence).

3.1.1. Noise effects on attentional tasks and Yerkes-Dodson law. Behaviorists Yerkes and Dodson (1908), in their experiments with discrimination learning in white mice, described the non-linear effect of punishment on the speed of habit formation. Later, Yerkes-Dodson law was applied to attentional research and interpreted in corresponding terms. Kahneman (1973), in the context of his resource theory of attention, summarized both empirical data and theoretical considerations in this field. In this paper, it is important that the effect of an external distracting noise on attention is non-linear and corresponds to Yerkes-Dodson law. Thus, noise may either interfere with or facilitate task performance, depending on its intensity and internal factors affecting arousal, such as motivation, extraversion, drowsiness, and so on. In other words, noise may be considered as both an interfering and a redundant stimulation.

3.1.2. Spatial effects of abrupt onsets and peripheral cues. Posner’s spatial cue paradigm is typically used for studying orienting of attention. A target stimulus is preceded by a cue signal, indicating the potential spatial location of a target. The cue can be either central or peripheral. It is assumed that the central cue can be used deliberately and that the peripheral cue (or abrupt onset) can be used mainly reflexively (Jonides, 1981; Yantis & Jonides, 1984). Consequently, a person can hardly ignore the peripheral cue (or abrupt onsets) unintentionally. This corresponds to what is considered to be the distraction of attention. It seems that involuntary orienting and distraction are two sides of the same coin.

It is already established that involuntary orienting typically demonstrates biphasic temporal dynamics, which may be described as the serial alternation between redundancy and interference effects. This biphasic pattern was initially described by Posner and Cohen (1984) and replicated in numerous studies (see Lupiáñez et al., 2006; Wright & Ward, 2008, for reviews). The first phase of orienting is accompanied by the facilitation of the response to the target at a cued location. The formal theory of the distractor corresponds to the redundancy effect. The second phase of involuntary orienting appears to start about 300 milliseconds after the cue onset is accompanied by the inhibition of the response to the target at a cued location. This phenomenon is typically termed the *inhibition of return (IOR)*. In terms of the formal theory of the distractor, the IOR corresponds to the interference effect. As some theorists have pointed out, a cued location is inhibited in order to take attention away from the previous location, in favor of exploring novel locations (e.g., Klein, 1988; Klein & MacInnes, 1999; Posner & Cohen, 1984).

It is natural to expect that the early redundancy effect for the cued location has to generate a concurrent interference effect for other locations. Nevertheless, Jonides (1981) tested the effects of peripheral cues on RT to targets at cued and uncued locations and found no interference (null effect) at uncued locations.

3.1.3. Target-distractor similarity in multiple-item displays: Attentional capture, redundant signal effect and guided search. Other phenomena corresponding to the Interference-Redundancy dichotomy are obtained in the visual search paradigm. The first phenomenon is known as *attentional capture* by a singleton. A singleton is an item differing from both target and other distractors due to its unique features such as color, shape, size or orientation, etc. It is established that the target's reaction time is slower if one of distractors is a singleton that captures attention involuntarily and, thus, distracts it from other items including the target (see Egeth & Yantis 1997, for review). In terms of this paper, attentional capture by a singleton can be considered as an interference effect.

On the other hand, a target may be found faster if there are several items with the same critical feature among distractors. Two classes of phenomena support this assertion. The first one is the *redundant signal effect*. It refers to a faster and more accurate discrimination or identification of a target amongst an array of items resembling the target. For example, it takes less time to respond as to whether the third letter is a B in a string BBBBB than in a string FKBJP. Notably, the redundant signal effects are obtained in both search and non-search tasks (Bjork & Estes, 1971; Estes, 1972; Grice & Gwynne, 1987; Johnson, 1986; Miller, 1982).

However, the facilitation effects of target-distractor similarities do not necessarily require a complete identity between items. In some cases, a partial similarity between target and distractor may serve to *guide the visual search* in a rather effective manner. In a study by Egeth et al. (1984), it was found that the search for a certain target (for instance, red O among red and black letters) depends on the number of similar distractors, rather than total amount of distractor items (e.g., on red letters only rather than red and black letters together). Wolfe (1992, 1994; Wolfe et al., 1989) in his visual search model stated that the similarity between distractors and targets in some critical features may serve to guide attention in the visual field by making a conjunction search partially parallel. In their experiments, Wolfe et al. (1989) found that the search for a three-feature conjunction may be even more efficient than a two-feature search, because it is guided by three parallel processes rather than two. Guided search phenomena indicate that the similarity between distractors and targets may be a source of redundancy effects in the visual search.

3.2. Structural (unit) effects

It is natural for our perception and memory to organize elementary experiences in ordered units which are useful for the holistic perception of objects and events, and for action. Nevertheless, there are numerous perceptual tasks in which certain features and elements are more relevant than whole units. Thus, in these tasks, other features and elements are considered to be distractors. Again, it appears that the effects of such distractors follow the Interference-Redundancy dichotomy. The common rule for distractor effects of this type is as follows; if both the target and the distractor are included in the same structural unit, then the distractor is likely to aid task performance, which then corresponds to the redundancy effect. In contrast, if the target and the distractor are not included in the same unit, then interference is more likely to occur. The following examples will illustrate that this rule extends to perceptual, semantic and response units.

3.2.1. Effects of perceptual units in visual search. There are two modes of the visual search of targets in visual arrays depending predominantly on stimulus characteristics and practice. In some cases, the search is carried out in a parallel way, with little participation of voluntary attention. This means that the distinction between the target and the distractors' perceptual units is salient enough. Manipulating the number of distractors has little or no effect on the search time that corresponds to the null effect of distractor. In other cases, when the distinction is not salient, visual search may be serial and therefore attentionally-demanding. It is well established that the addition of distractor items to an array in the serial search typically yields a search time increment. The phenomenon is known as the *'set size effect'*. This corresponds to the interference effect of a distractor. Here, distractors and targets refer to different perceptual units. Nevertheless, situations in which the addition of distracting items improves target detection are also described in visual search literature. Pomerantz (2003; Pomerantz et al., 1977) has investigated *configural superiority effects* in the visual search. Configural superiority effects typically take place when the spatial locations of targets and additional distractors allow their perceptual grouping in one 'good' gestalt, or perceptual unit. That unit is salient enough to summon the involuntary shift of attention to it and, hence, to the target. A visual search under such configural superiority is almost parallel (Pomerantz, 2003). In my terms, this reflects the redundancy effect of a distractor on the target detection.

3.2.2. Distractor effects in reading: the Reicher-Wheeler paradigm. It was mentioned above that adding distractors to visual displays may disrupt or facilitate performance both in search and non-search tasks. When flanked by irrelevant items, the target's detectability or discriminability is typically disrupted (Eriksen & Eriksen, 1974). This flanker interference is sometimes termed as "crowding" (He et al., 1996). The crowding effect may also arise in letter perception. However, it may be opposed by the specific redundancy effect, which originates from a semantic rather than a purely sensory source. Thus, Reicher (1969), in his classical study, found out that his participants tended to discriminate briefly presented letters more accurately in words than in quadrigrams and in letter alone conditions. A similar result was replicated by Wheeler (1970). The similar improvement for speed rather than accuracy of recognition was earlier discovered by Cattell (1886). This *word superiority effect* may be considered to be the typical redundancy effect of distractor. Fine (2001), in her experiments with lateral masking, found flanker interference in both senseless letter strings and in word superiority effects.

3.2.3. Response compatibility: Stroop and flanker tasks. The color-word Stroop task (MacLeod, 1992; Stroop, 1935) and the flanker task (Eriksen & Eriksen, 1974) are the typical paradigms for investigating the attentional function in resistance to distraction. Both tasks are based on manipulating the compatibility between reactions assigned to targets and distractors. Both interference and redundancy effects may be obtained in these two tasks. It appears that certain effects depend on whether the target and distractor belong to the same or different response units. If a target A requires response α and distractor A' also corresponds to α, then response α should be performed more readily (faster) when the target A is presented alone. . This corresponds to the redundancy effect of distractor A'. In contrast, if a target A requires response α, while concurrent distractor B' corresponds to the antagonistic response β, then α should be performed slower or possibly replaced with β. This corresponds to the typical interference effect.

In the case of the Stroop task, this common rule manifests itself as the inhibition of the response to ink color in color-word conflict and the facilitation of responses in color-word congruency (but see MacLeod, 1991, for notions about experimental replications of facilitation in the Stroop task). In the flanker task, the distractor effect depends on the response compatibility between the central target symbol and the flanker distractor symbols. If both the target and the distractor involve the same response (e.g. pressing a key with the left hand), then the redundancy effect is more likely to take place. On the other hand, if the target and distractor concurrently appeal to opposite responses assigned by instruction, then interference is more likely to occur.

3.3. Correlation effects

In the perception of dynamic events, a person has to confront numerous variations in stimulation. Both relevant (target) and irrelevant (distracting) features of events are variable. Theoretically, their independent combination should produce a large number of ‘degrees of freedom’ for the possible interpretation of any event. Consequently, the perceptual system should either block distractors totally or reduce uncertainty to deal with such variability. Of course, our natural environment is not a fully entropic system. In other words, in the real world there are only a few features which are fully independent. The correlation between distinct features is rather frequent. It appears that highly correlated feature conjunctions are the appropriate material for learning. If the total blocking of distractors is impossible, then they may serve to aid target performance should a reliable correlation exist between them. The common rule for the distractor effects of the correlation type may be formulated as follows. If the target and the distractor vary independently (uncorrelated), then task performance should be impaired as compared to the baseline, or constant distractor. Therefore, interference is expected in a null correlation between the distractor and the target. If there is a significant correlation between target and distractor (meaning that some conjunctions of their properties are frequent and some are rare) then the rule should be as follows: (1) the redundancy effect is expected for frequent conjunctions and (2) the interference effect is expected for rare conjunctions.

3.3.1. Effects of feature correlation on discrimination: Garner task. In the series of experimental studies in 1960-70s concerning the concept of integrality, it was established that many object features (such as color, shape, size, orientation, etc) may interact in an interference-redundancy fashion. The most significant of these is the series of experiments by Garner (1969; Garner & Felfoldy, 1970). His participants had to perform speeded[3] classification by sorting cards of certain objects in accordance with a target dimension. In the control condition, the target dimension varied while the distractor had a constant value. In the other conditions, the target and distractor varied orthogonally. In the third condition, they varied in correlation. It was observed that in some feature combinations participants tended to be able to classify faster in correlated conditions than in the control one. In contrast, they tended to classify objects in the orthogonal condition slower than in the control one. These results completely correspond to the 'Interference-Redundancy' dichotomy. However, that pattern of results was obtained in particular target-distractor feature combinations such as value-chroma and vice versa. In other feature combinations such as circle diameter and orientation there were no pronounced distractor effects. Another finding by Garner was that both interference and redundancy effects took place when both target and distractor features belonged to the same rather than different objects. Garner interpreted his results in terms of the integrality and the separability of object dimensions.

3.3.2. Probabilistic effects of cues. Distractors and targets may correlate not only as simultaneous features of the same objects. They also may correlate as successive events in time. Such successive correlation may be also learned without awareness through a number of serial trials and utilized as a source of redundant associations. These associations allow us to predict some critical properties of the target on the grounds of the prior distractor. Such priming distractors are often considered to be perceptual or attentional cues which affect performance in spite of experimental instructions to ignore them. The way in which the cue affects performance is a matter of probability. In accordance with the above rule for correlation effects, frequent cue-target sequences should yield redundancy effects and rare cue-target sequences should yield interference effects. Empirical evidence for this rule was obtained in a set of experiments with spatial cueing. Thus, Bartolomeo et al. (2007) manipulated the probabilities of peripheral cues at the stimulus onset asynchrony (SOA) of 600 to 1000 msec. They demonstrated that highly probable peripheral cues had a positive (redundant) effect on RT by eliminating an involuntary IOR effect to a target typical for long SOAs. In contrast, improbable peripheral cues had a negative (interference) effect on performance at cued locations by amplifying IOR. More striking results were obtained by Lambert et al. (1999). In one of their experiments, they tried to form spatial associations between targets and bilateral letter cues. In the end, they observed a biphasic pattern of facilitation at short SOA and inhibition at long SOA, typically taking place in exogenous orienting by non-informative spatial cues. Both Bartolomeo et al. (2007) and Lambert et al. (1999) used post-experimental questionnaires to test whether their participants had been aware of cue-target correlation or not. They concluded that the orienting pattern did not depend on awareness. This notion is critical in the context of this paper, because it indicates the irrelevant character of the cue-target correlation for participants. Such irrelevancy corresponds to distraction in the sense adopted at the beginning of the paper.

4. General Rule of the formal theory of the distractor

In the previous section, it was demonstrated that distractors may affect tested performance in both interference and redundancy ways in various tasks. It was established that effects depend on specific task conditions. For the formal theory, it is necessary to state the unitary rule that would be suitable for any task. This rule should predict the distractor effect in any task based on target-distractor analysis *a priori*.

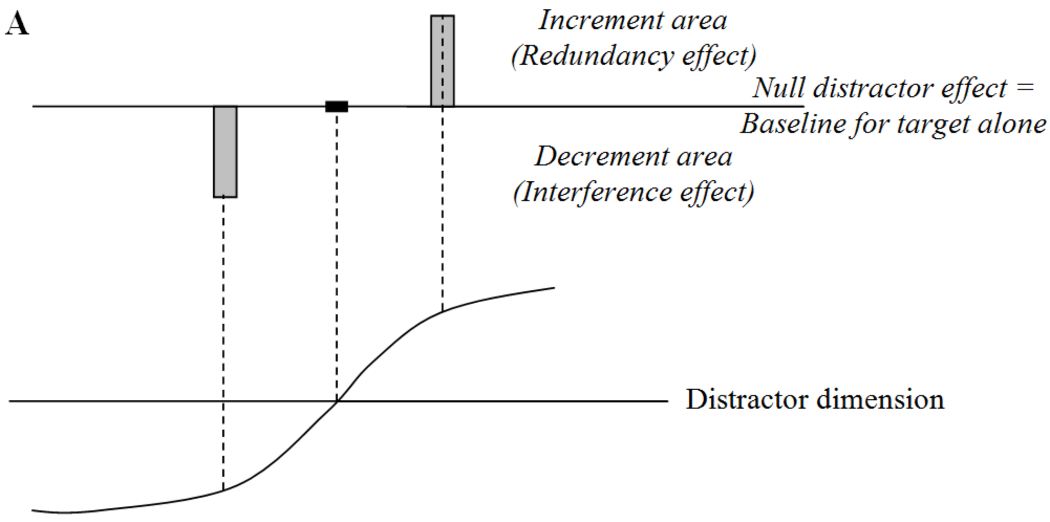
In attempt to state the General Rule, I turn to Shannon’s (1948) mathematical theory of communication, mentioned above. The theory is a rather generalized formal model describing and measuring the information load of a message on a transmitting channel. As soon as stimulus display in perceptual tasks may be considered as a message, this model becomes applicable for the analysis of distractor effects as well. The two key terms of the model are ‘entropy’ and ‘redundancy’. According to the model, the addition of symbols to a message increases entropy. A growth in entropy yields an increased information load on the transmitting channel. Analogously, the adding of distractors (defined by physical intensity, number of items and their features or variability) should cause the total entropy to increase with a resulting increment in load and a loss in performance. The loss in performance is termed above as the *interference effect*. However, the theoretically predicted amount of entropy may be reduced if there is a systematic relationship between certain elements of a message. Such systematic relationships are reflected in the integral measure of *redundancy*. Redundancy allows the unloading of the channel by the compression of a message. There may be analogy between the information redundancy of a message and the stimulus redundancy in an attentional task. A positive relationship between the distractor and the target reduces the total entropy and allows the collection of the target and all the related irrelevant features together, in order to subsequently 'compress' them into one unit of information. The total weight of this unit should rise after such collection and compression. Redundancy effects result from such compression and the high information weight of target-and-related distractor units.

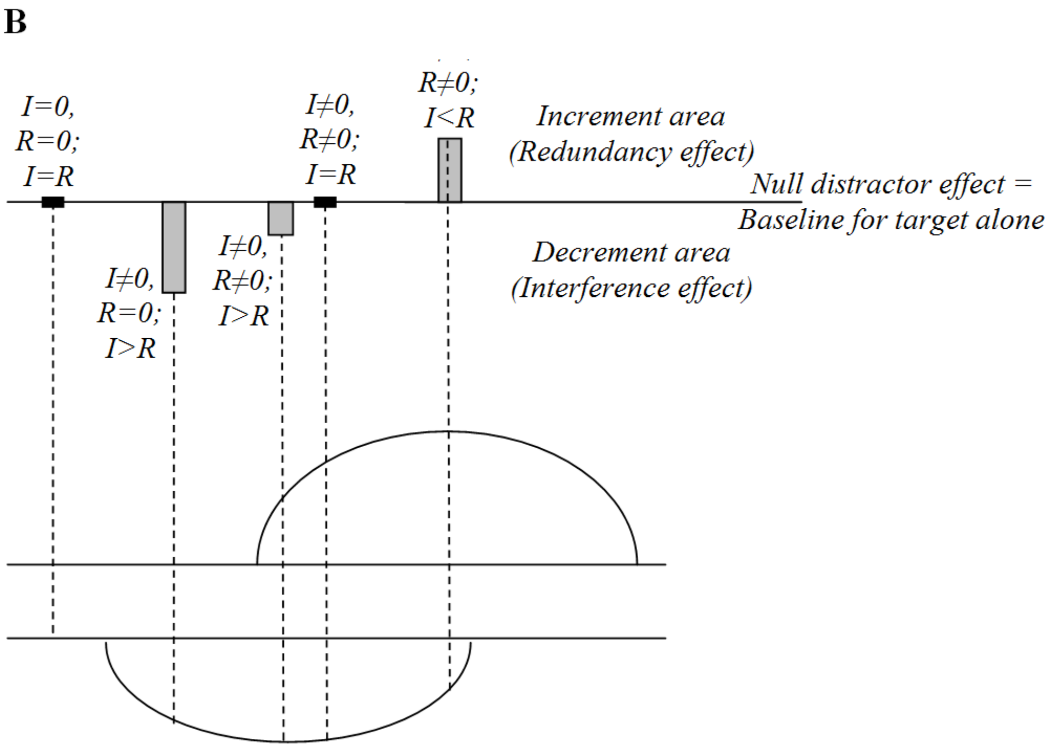
The General Rule for the formal theory of the distractor may be stated on the grounds of the above analysis. According to the General Rule, the *interference effect is probable if the adding of the distractor supports a growth in entropy; in contrast, the redundancy effect is more likely if the distractor redundancy exceeds the amount of entropy induced by this distractor.*

5. Speculations on the nature of distractor effects: Single-process vs dual-process framework

In the present section, I shall address two versions of the formal model that may be useful for understanding the nature of decrements and increments of performance in the presence of a distractor.

Figure 1. A graphical presentation of (A) single-process and (B) dual-process frameworks for the explanation of distractor effects





The first viewpoint on the nature of distractor effects may be termed as the *single-process framework*. It suggests that the distractor is processed by a single mechanism over the whole range of its variation. The overall effect depends on a particular distractor value in this range. Distractors are processed in the interference-like mode in one region of the critical dimension, and are processed in a redundancy-like mode in the other region. The single-process model also implies a 'transition zone' or 'transition point', where interference is not strong enough for decrement and redundancy is not strong enough for the facilitation of performance. A null effect of the distractor is predicted by the model in the ‘transition zone’. Summarily, a single-process account of the distractor is shown at Figure 1A. It is important for the single-process framework that the subtraction of performance level under distractor’s conditions from the baseline provides a pure measure of interference or redundancy effect.

The second approach to distractor effects may be termed the “dual-process framework”. This framework implies the existence of two sets of processes. The first set includes processes resulting in interference (I-processes), and the other set includes processes which extract and utilize redundant information about the distractor and modify task performance (R-processes). I-processes treat distractors as separate elements of a message, while R-processes seek bases to somehow integrate and compress related distractors and targets in highly significant redundant units. The two sets of processes are considered as independent but partially overlapping at a certain region of the distractor dimension. They are illustrated in Figure 1B as the two parallel axes, I and R. If the I- and R-processes do not share a common region of the distractor dimension, then any change of performance at any point of the dimension should be attributed to only one set of processes. This case does not principally differ from what is predicted by the single-process model. In contrast, if I- and R-processes share a common region, then the dual-process framework predicts that the overall distractor effect depends on the I and R magnitude ratios at a given point. Thus, if the magnitude of I exceeds the magnitude of R, then target performance should be impaired. In contrast, if the magnitude of R exceeds the magnitude of R, then target performance should be improved. Moreover, the dual-process framework predicts two possible sources of null effects. The first possible source is in insufficient magnitudes of both I- and R-processes. A similar explanation is offered by the single-process framework. The second source of a null effect may be termed as ‘mutual annihilation’. This is where I and R may achieve equal magnitudes at certain points, and serve as a counterbalance for each other. All predictions of dual-process framework are shown in Figure 1B.

Although the dual-process model is more general and describes a wider range of target-distractor interactions, it is still not rid of at least one serious problem. The problem is that the model implies an inevitable mixture of interference and redundancy effects at a region where I and R are overlapping. In other words, the difference between the baseline and distractor conditions cannot be considered as a pure measure of interference or redundancy effect. It appears that the dual-process framework needs a special procedure of empirical dissociation between two sets of processes and their further quantitative measurement. Such useful dissociations are made in other influential dual-process models such as the signal-detection theory or the process dissociation paradigm (Green & Swets, 1966; Jacoby, 1991). It is likely that such dissociation procedures will require certain assumptions like the ones made by the aforementioned dual-process models. Undoubtedly, the development of such a dissociation would help to provide significant progress both in the experimental research of distraction and in its applications.

Moreover, it appears that there are no unitary formal criteria for adopting a single framework for all distractor effects. When deciding which model is preferred, a theorist must return from formal description to the content analysis of distractors in the context of a particular theory. Thus, some processes may follow the single-process model, while others may follow the dual process one. The decision appears to depend on a particular essential mechanism, which ought to underlie the processes according to the particular theory.

Single-process models are rather economical, intuitively clear and, hence, available for many distraction phenomena. It appears attractive to use the single-process interpretation for the Yerkes-Dodson pattern of noise effect on performance. It is natural to suppose that noise affects performance through the single process of nonspecific arousal. According to the hypothesis suggested by Easterbrook (1959) and supported with reserve by Kahneman (1973), there is a direct association between arousal and the attentional selectivity which defines operating targets and distractors. The selectivity of attention tends to increase with arousal. In other terms, arousal increments are associated with a narrowing focus of attention. If the start level of arousal is low, then the additional arousal by noise improves performance by narrowing the focus of attention, which allows one to cope with irrelevant information. If arousal is high, then a further narrowing of the attentional focus should impair performance, since it prevents the organism from noticing useful cues. Another single-process account is suitable for distractor effects in the Stroop task. It is intuitively reasonable that there is a unitary process that underlies both color-word interference and facilitation. It is presumably word reading which is more automated andfaster than the color encoding required for successful target feature naming. The distractor effect generated by an irrelevant word depends on its congruency with the target color.

On the other hand, there are many examples in which the redundancy effects simply cannot be explained by the mechanisms which underlie the interference effects. For such cases, dual-process explanations must be used. Thus, the dual-process framework is more available for word superiority effects. It implies that an automatic recognition of the whole word, the source of R-processes, is added to separate- letter processing, which is the source of

I-processes (crowding). It is likely that a similar redundant process underlies the configural superiority effects in the visual search. As was proposed by Pomerantz (2003), such a redundant process may underlie the occurrence of emergent object features.

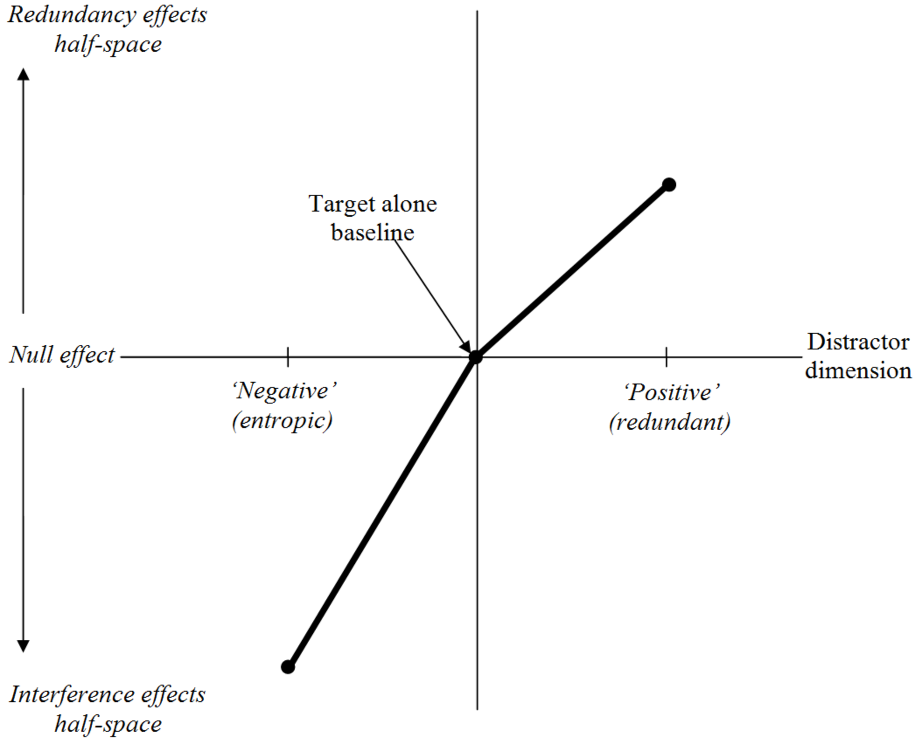
The relative simplicity, economy and intuitive likelihood of single-process models are still not exhaustive criteria to adopt them uncritically. There are at least several examples found in literature when intuitively appealing single-process explanations are replaced by the more complex dual-process ones after detailed analysis. Thus, some theorists recently discussed the Stroop interference and facilitation as the results of two distinct processes rather than automatic reading alone (Lindsay & Jacoby, 1994; MacLeod, 1991, 1998). Following this viewpoint, the Stroop interference and facilitation should be formally described by the dual-process model. Another example concerns the biphasic pattern of orienting towards an irrelevant peripheral cue, including the facilitation of responses within 300 milliseconds SOA and the inhibition of return (IOR) at longer SOAs. From the single-process viewpoint, the exogenous orienting of attention over time and space may be considered as underlying both early facilitation and later inhibition. Alternatively, Danziger and Kingstone (1999) suggested that facilitation and inhibition result from different processes. The facilitation of response originates from exogenous orienting of attention, as was proposed by traditional theories. IOR, according to Danziger and Kingstone (1999), is an independent process separated from the orienting of attention. Moreover, Danziger and Kingstone (1999) hypothesized that IOR may arise at much more short SOAs than standard 300 milliseconds, but it is typically masked by an exogenous orienting of attention. In terms of the dual-process framework, that means that attentional orienting is a source of redundant processes (R), and IOR is a source of interference (I). The total cue effect on reaction time depends on their magnitudes ratio at certain SOAs. Thus, at short intervals the redundant processes of attentional orienting are typically strong enough to exceed the concurrent interference by IOR. Later, the IOR effect becomes more pronounced with the extinction of exogenous orienting. Notably, Danziger and Kingstone (1999) were able to provide an experimental procedure of dissociation (‘unmasking’) between attentional orienting and IOR. Unfortunately, their procedure is highly task-specific and may only with difficulty be transferred to other paradigms directly. Posner and Cohen (1984) who primarily described the biphasic pattern of visual orienting also proposed the dual-process rather than the single-process interpretation of this pattern.

6. Distractor profiles (DPs)

6.1. DP construction

As demonstrated above, distractor effects of any type may be described throughthe Interference-Redundancy dimension. Hence, it is natural that distractor effects in any task may be quantified and estimated in a similar fashion. In my opinion, the most effective tool for such unified quantification and esteem is the visualization by a simple plot called a Distractor Profile (DP).

Figure 2. Distractor profile (DP) common view



The general view of DP is presented in Figure 2. The X axis denotes a dimension in which the distractor is varied. The Y axis denotes the magnitude of a distractor effect. The null point of this coordinate system corresponds to the baseline level achieved in target-only conditions. Consequently, the positive half-space above the X axis corresponds to the redundancy effects, and the negative half-space below the X axis corresponds to interference effects. Finally, the X axis level corresponds to the null distractor effect. It is more problematic in some cases to define what is to be placed on the left and on the right of the Y axis. What values of distractor dimension should be considerd 'negative' and what values should be considered 'positive'? The single answer can be found only from the formal viewpoint provided by the General Rule stated above. In terms of the classical theory of communication (Shannon, 1948), it is natural that negative values are those which increase the information entropy (or uncertainty) of a system. Correspondingly, positive values are those which decrease entropy (and thus increasing certainty, or redundancy). In other words, distractors that provide additional alternatives for perception and/or action in comparison with the target alone are 'negative'. Distractors reducing the number of additional alternatives by coinciding in some characteristics with the target are typically 'positive'. Of course, a theorist should define the positivity or negativity of distractor conditions analytically prior to experimental data. It is a serious logical error to define positive or negative values *a posteriori*, through the empirical distractor effect obtained in a certain condition. Assertions such as, 'the distractor is negative because it summoned the interference effect' or, 'the distractor is positive because it summoned the redundancy effect' are senseless, since they imply a vicious circle in the definitions of distractors and distractor effects. In their hypotheses, experimental designs and DPs, researchers should define the distractor as positive or negative on the grounds of formal and essential theoretical considerations. Formal considerations are predominantly based on the General Rule. Essential considerations may be taken from theories predicting certain extensions and limitations of processes, which underlie the performance of an individual task. Then an experiment is conducted in order to empirically establish the distractor effects on performance. In the end, in DPs the researcher should match empirically measured distractor effects and theoretical considerations and predictions.

Measures of distractor effects in positive and negative values of the distractor plotted on DP may be achieved by a method similar to the cost-benefit analysis in reaction time experiments (Posner, 1978; Posner & Snyder, 1975). It consists of subtraction efficiency rates in baseline and distractor conditions. The roles of minuend and subtrahend depend on the character of a particular variable used as an efficiency rate. If there is a positive interrelation between the magnitude of a variable and efficiency, then the baseline is subtracted from the distractor condition. For correct responses and sensitivity measures such as d', there is a positive interrelation between magnitude and efficiency. In contrast, if there is a negative interrelation between magnitude and efficiency then the distractor condition is subtracted from baseline. For reaction times, error rates and threshold measures, there is a negative interrelation between magnitude and efficiency. Both subtraction procedures should result in the negative value of the distractor effect if the distractor condition is performed more poorly than the baseline, and positive value if the distractor condition is performed better than the baseline. Consequently, a negative value corresponds to the interference effect and a positive value corresponds to the redundancy effect.

As soon as the distractor effects are computed, they may be placed on DP with respect to distractor conditions. Finally, obtained point marks should be tied with the null point by straight lines. It is important that straight lines do not imply any linear interpolation between the tested values of the distractor. Rather, they are simply more useful for visualization than point marks alone, since they form an easily recognized profile.

6.2. Interpretations of DPs

The interpretation of DP in any individual experiment depends on many factors concerning particular tasks and their conditions. Nevertheless, formal distractor theory permits one to discard many particular circumstances. The only formal factors affecting interpretation are the shape of DP and the single- vs dual-process framework.

Eight examples of prototypical DPs are shown in Figure 3. The effect of the 'negative' distractor is denoted as *a*, while the effect of the 'positive' distractor is denoted as *b*.

1. $a < 0, b > 0, |a| = |b|$. This case is shown in Figure 3A. It reflects the symmetrical interference and redundancy effects elicited by 'negative' and 'positive' distractors.

2. $a < 0, b > 0, |a| > |b|$. This case is shown in Figure 3B. It reflects the asymmetrical effects elicited by 'negative' and 'positive' distractors, where the interference effect is supreme over the redundancy effect.

3. $a < 0, b > 0, |a| < |b|$. This case is shown in Figure 3C. It reflects the asymmetrical effects elicited by the 'negative' and 'positive' distractors, where the redundancy effect is supreme over the interference effect.

In terms of the single-process framework, cases (1), (2) and (3) are equal. They correspond to the typical Interference-Redundancy dichotomy and demonstrate that the manipulated distractor dimension is in some way critical for controlling the target perception and/or reactions. Nevertheless, in terms of the dual-process framework, there may be alternative interpretations, except those by the single-process framework. It allows the concurrent competition of I- and R-processes. Thus, in all cases, R-processes should be supreme over I-processes in terms of magnitude, in order to resist interference and to achieve a positive redundancy effect.

4. $a < 0, b < 0, |a| = |b|$. This case is shown in Figure 3D. It reflects the equal interference effects of both 'negative' and 'positive' without any evidence of redundancy. In terms of both single- and dual-process frameworks, this means that the manipulated distractor

dimension is not redundant at all, or, at least, the certain ‘positive’ value of distractor failed to reach the redundant range of the dimension.

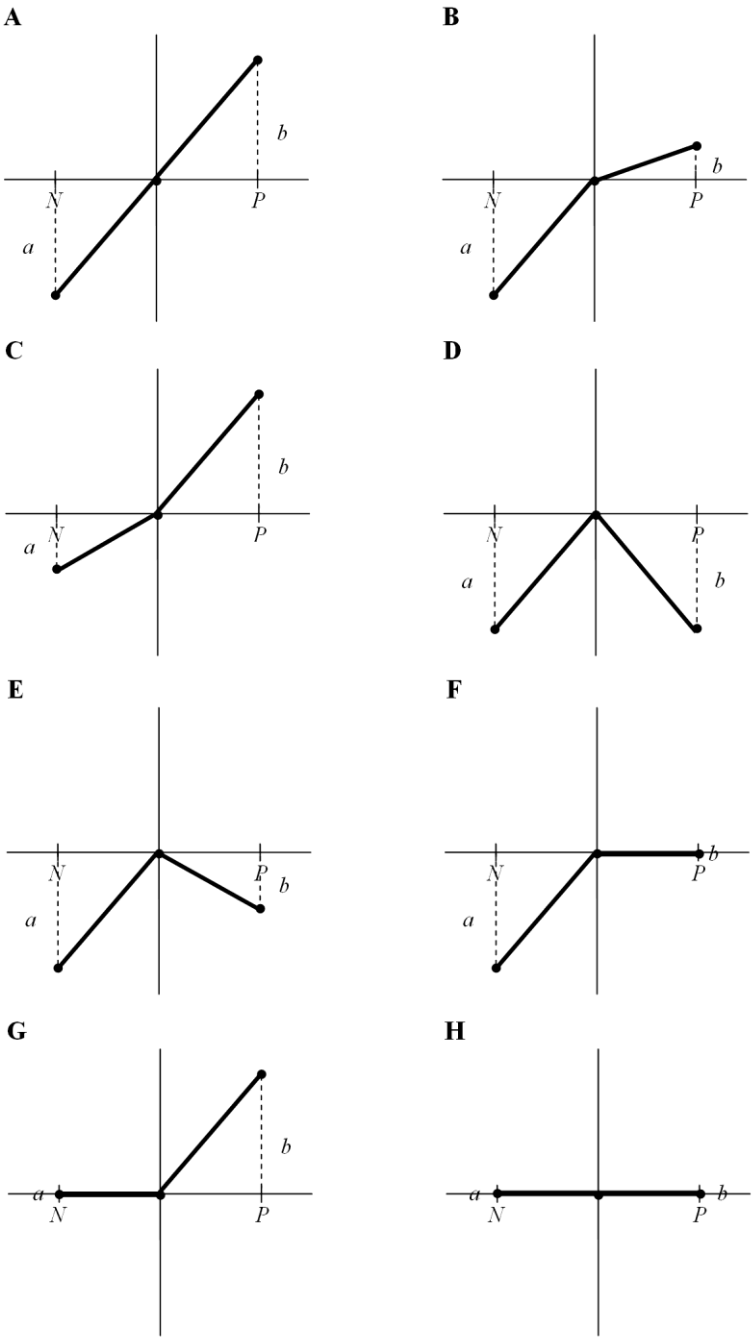
5. $a < 0, b < 0, |a| > |b|$. This case is shown in Figure 3E. It reflects the interference effects elicited by both ‘negative’ and ‘positive’ distractors, but the interference effect of the ‘positive’ distractor is weaker than that of the ‘negative’ distractor. In terms of the single-process framework, this case may suggest either a deviation in the level of interference, or a subsequent transition into the redundant range of the distractor dimension. In contrast, the dual-process framework allows competition between relatively strong I- and relatively weak R-processes.

6. $a < 0, b = 0$. This case is shown in Figure 3F. It reflects the interference effect elicited by the ‘negative’ and null effect by the ‘positive’ distractor. In terms of the single-process framework, this means that the intermediate range between interference and redundancy is achieved. In terms of the dual-process framework, this means that there is a mutual annihilation between I- and R-processes with equal magnitudes. Moreover, in terms of both frameworks, a null effect may be achieved beyond distraction, that is, in the successful ignoring of some distractor values. On the other hand, a DP of this sort may be obtained if the baseline performance is near perfect and cannot be improved by redundant information.

7. $a = 0, b > 0$. This case is shown in Figure 3G. It reflects the null effect elicited by the ‘negative’ and the redundancy effect by the ‘positive’ distractor. In terms of both frameworks, this means that the target is processed without distractor-related limitations but redundant information can be still extracted. Alternatively, the null effect of the ‘negative’ distractor may be achieved if the baseline performance is near chance.

8. $a = 0, b = 0$. This case is shown in Figure 3I. It reflects null effects in both ‘negative’ and ‘positive’ distractor conditions. It is most likely that a DP of this kind may be achieved only in the successful ignoring of a distractor.

Figure 3. Variants of Distractor Profiles (DPs)

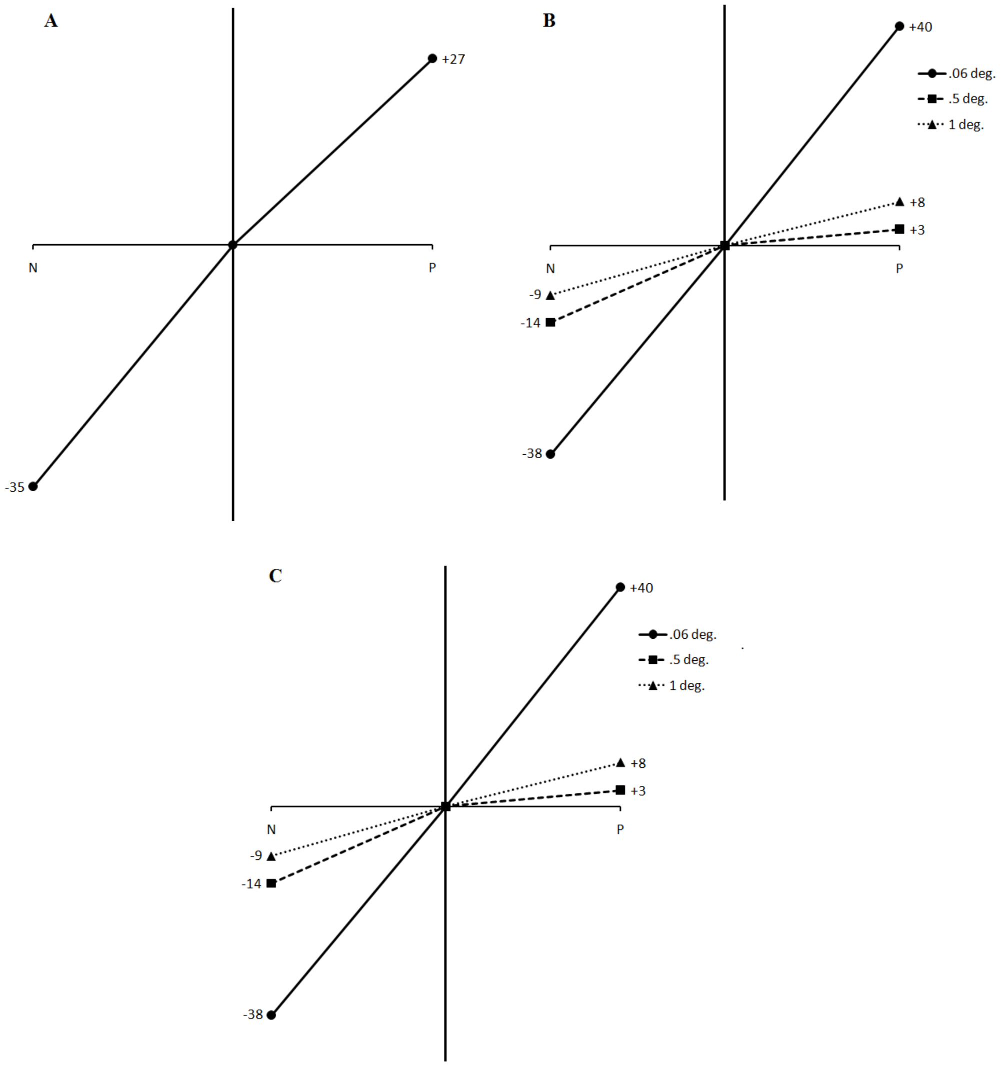


(A), (B), (C) contain DPs reflecting both the interference and redundancy effects with corresponding 'negative' and 'positive' distractors ; (D), (E) contain DPs reflecting the interference effects with both 'negative' and 'positive' distractors; *(F) an interference effect without redundancy effect; (G) a redundancy effect without interference effect; (H) null effects with both 'negative' and 'positive' distractors.*

6.3. Examples of DP usage

In this section of the paper, I shall address several frequently cited experiments with distinct distractor effects in terms of DPs. Three experiments were selected, each representing one of the three distractor domains mentioned above.

Figure 4. DPs for the data of attentional experiments



(A) Posner and Cohen (1984); (B) Eriksen and Eriksen (1974), and (C) Garner and Felfoldy (1970).

6.3.1. Effects of peripheral information: Posner and Cohen (1984). In one of their experiments, Posner and Cohen (1984) showed the biphasic effect of the peripheral abrupt onset on spatial shifts attention. The experimental procedure included manipulations with cued vs. un-cued target locations and short (100 msec) vs. long (650 msec) SOAs. In formal terms, target presentation at uncued locations is considered to be the baseline condition, while the cued targets are considered as the distraction condition, since the cue presentation implies the unpreventable involuntary visual processing of irrelevant events at the cued region.

Posner and Cohen (1984) observed the acceleration of responses to uncued targets with longer SOAs. This effect might occur due to the nonspecific and non-spatial alerting effects elicited by the cue (Niemi & Näätänen, 1981; Posner, 1978). They also found no change in RT to the cued targets with SOA change. However, the most important finding was that responses were faster to cued vs. uncued targets at a short SOA, and were slower at a long SOA. Thus, Posner and Cohen (1984) demonstrated that both facilitation and inhibition may occur in response to peripheral cues depending on the SOA. Table 1 contains the raw RT values reconstructed from the plot provided by Posner and Cohen (1984) and the inferred values of distractor effects. The DP for their data is presented in Fig. 4A. The shape of the DP corresponds to the prototype depicted in Figure 3A, illustrating an almost symmetrical interference and redundancy effects with the same distractor under different temporal conditions.

Table 1. Proximate RT data (in milliseconds) by Posner and Cohen (1984) extracted from the plot (Fig. 32.3, page 537) and inferred distractor effects.

Peripheral cue (distractor) condition	SOA	
	Short	Long
Uncued (baseline)	525	460
Cued	498	495
‘Uncued – Cued’ RT (distractor effect)	+27	-35

It is necessary to explain placing long and short SOAs at ‘negative’ and ‘positive’ distractor positions of DP plot. An explanation may be made on the grounds of Posner’s dual-process theoretical consideration of the biphasic pattern of spatial selection. It is rather obvious that an abrupt onset at a certain location serves to mark this location out among others. This kind of marking reduces the target spatial entropy. Consequently, a peripheral cue at a certain location should be considered as a ‘positive’ distractor. According to Posner and Cohen (1984), it is natural for attention to return to the fixation point if the target expectation is too long. Meanwhile, the target entropy at a cued location returns to its initial state. Besides, attention tends to exclude the previously attended position from the list of preferable locations to return. This is made in order to facilitate exploring novel locations. It is the conflict between the suppression of the previously attended location and the actual target location that causes the entropy increment and subsequent interference, termed the inhibition of return (IOR). Hence, a peripheral cue should be considered to be a ‘negative’ distractor at long SOAs.

6.3.2. Flanker task: Eriksen and Eriksen (1974). In their experiment, Eriksen and Eriksen (1974) tested the effects of flanker distractors on central target responses. Their participants had to perform a speeded identification of central letters surrounded by letter flankers containing similar or dissimilar letters. Flankers could be response-compatible, response-incompatible with the target, or neutral. In a compatible condition, participants had to respond to a target letter in the presence of flankers assigned to the same response key. In the incompatible condition, they had to respond to the target letter in the presence of flankers assigned to the opposite response key. In terms of the formal theory, compatible flankers may be considered as a ‘positive’ distractor, while incompatible ones may be considered as a ‘negative’ distractor at DP plot. Flanker letters, both similar and dissimilar to the target, which are not assigned to any response, should be considered as the baseline condition[4]. Letter spacing was manipulated at three levels. The RT values in each condition reconstructed from the plot provided by Eriksen and Eriksen (1974) and the inferred distractor effects are shown in Table 2.

Table 2. Proximate RT data (in milliseconds) by Eriksen and Eriksen (1974) extracted from the plot (Eriksen, Eriksen (1974), page 146, Fig.1) and inferred distractor effects.

		Center-flanker response compatibility		
Letter spacing		Compatible	Neutral (baseline)	Incompatible
.06 deg.	RT	460	500	538
	Distractor effect	+40	0	-38
.5 deg.	RT	447	450	465
	Distractor effect	+3	0	-14
1 deg.	RT	435	443	452
	Distractor effect	+8	0	-9

[4] Unfortunately, Eriksen and Eriksen (1974) did not manipulate the similarity and response compatibility in completely independent ways; see Rouder and King (2003) who estimated the contributions of both the similarity and the response competition to flanker effects

The neutral condition RT is obtained by averaging similar and dissimilar center-flanker conditions.

Figure 4B illustrates the corresponding DPs. The three lines reflect the three spacing conditions. As can be seen from the plot, the most powerful distractor effects were obtained for a minimum letter spacing of *.06* degrees (solid line). It has a rather symmetric shape, corresponding to the prototype depicted in Fig. 3A. Furthermore, the DP slopes tend to decrease systematically with letter spacing (dotted lines). That reflects a gradual decline in the distracting potential of flanker letters with distance. As can be seen from *.5* degrees DP, the interference effect of the ‘negative’ incompatible flanker tends to persist in this spacing condition, while the redundancy effect of the ‘positive’ compatible flanker tends to reach null. In the maximum spacing of *1* degree, both interference and redundancy effects appear to reach null, corresponding to the prototype depicted in Fig. 3H.

6.3.3. Feature correlation: Garner and Felfoldy (1970). Garner and Felfoldy (1970) have been studying the integrality of elementary object dimensions such as basic color characteristics (chroma and value). Their participants had to perform a speeded classification task by sorting cards of objects into the two piles in accordance with the target dichotomous dimension (e.g. chroma) while ignoring another one (e.g. value). There could be three sorting conditions. In the first condition, only the target dimension varied across cards while the distracting dimension was constant. In the second condition, both target and distractor dimensions were correlated. In the third condition, dimensions varied orthogonally.

Table 3. Speeded classification time data (in seconds) by Garner and Felfoldy (1970), Experiment 1 (extracted from Garner, Felfoldy (1970), page 230, Table 1) and inferred distractor effects.

		Target-distractor correlation		
Target dimension		Correlated	One dimension (baseline)	Orthogonal
Chroma	RT	13.24	14.22	17.49
	Distractor effect	+.98	0	-3.27
Value	RT	13.73	15.09	18.55
	Distractor effect	+1.37	0	-3.46

In formal terms, the target only condition should be considered as the baseline level of performance. The correlated condition should be considered as a ‘positive’ distractor since target redundancy is increased under this condition. A highly correlated item should activate a unit corresponding to the relevant feature only and an integral unit for both correlated features. In contrast, orthogonal condition should be considered as ‘negative’ one since total entropy is increased. In the latter case, the two integral units activate along with the relevant feature unit. One such integral unit corresponds to the same response and another one corresponds to the opposite. It is the conflict between two units that causes an increase in entropy.

Table 3 contains raw data corresponding to one of the experiments by Garner and Felfoldy (1970) with chroma and the value of the same object as the target dimension. Moreover, it contains the outline distractor effects under ‘negative’ and ‘positive’ conditions. DPs for both features are presented in Figure 4C.

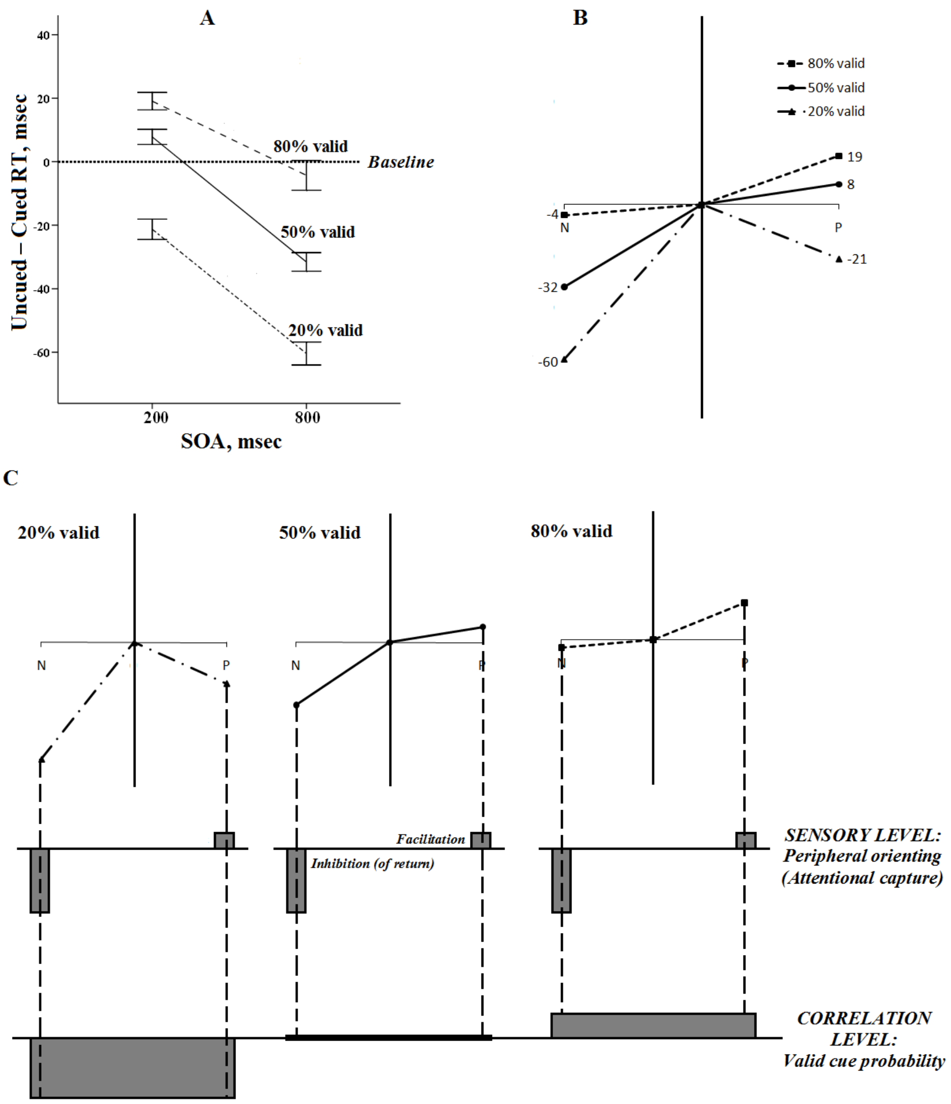
Indeed, ‘negative’ and ‘positive’ distractor conditions yielded interference and redundancy effects correspondingly. The two analyzed features have relatively the same configurations of DP, with more pronounced interference effects.

7. Modulating distractor effects: Hierarchical hypothesis

It is typical for real-world perception that sensory, structural and correlational features of distractors and targets vary concurrently. Thus, it is useful to describe their probable interaction in the formal terms introduced above.

Results of empirical studies allow a hypothesis that the distractor effects of the three above classes do not simply belong to different domains of perceptual and attentional processes, but they also may form a kind of hierarchy. This means that the structural features of perceptual or response units may modulate sensory input effects and may also be modulated by distractor-target correlations. Therefore, sensory input and structural and correlation effects may be considered to be specific manifestations of lower, middle and higher levels of cognitive systems which control the processing of unattended stimuli.

Figure 5. Modulating peripheral cue effects by valid cues probability in an experiment by Gusev et al. (2010)



(A) 'Uncued – Cued RT' as a function of SOA and valid cue probability extracted from raw data (error bars denote ±1 SEM); (B) DPs for the same result; (C) decomposition of distractor effects brought by SOA variation and valid cue probability in accordance with the hierarchical hypothesis.

Several studies illustrating this hypothesis can be found in literature. For example, Weisstein and Harris (1974) found that visual masking did not interfere with the discrimination of line orientation if both the target line and the subsequent mask shape formed a 3D-like configuration. That means that a rather severe low-level sensory interference (masking) may be modulated by a higher-order structural redundancy (configural superiority). Falikman (2002, Gorbunova & Falikman, 2010) came to a similar conclusion. In experiments with the rapid serial visual presentation (RSVP) paradigm, she found that word superiority effects (which refer to the structural redundancy effect) may attenuate an attentional blink effect that is typically associated with masking-induced interference.

There is also various evidence which shows that correlation distractor effects may modulate sensory input ones. In the study by Bartolomeo et al. (2007) mentioned above, it was established that the magnitude of IOR depended on the valid cues probability. IOR magnitude tended to increase under rare valid cues condition and tended to diminish under the frequent valid cues condition. In terms of the formal theory of a distractor proposed here, IOR amplification in the first condition may be described as the result of the addition of two interference tendencies elicited by the IOR itself and negative correlation between cue and target locations. In contrast, the attenuation of IOR in the latter condition may be interpreted as the result of the confrontation and mutual annihilation of the IOR-induced interference effect and redundancy effect due to the high correlation between cue and target locations. Gusev, Kingsep, & Utochkin (2010) replicated a result by Bartolomeo et al. (2007) regarding IOR and found evidence that an early facilitation effect does also depend on the valid cues probability. According to their data, facilitation increases in high valid cues probability and reverts to reach the inhibition effect in low valid cues probability. Again, this result can be explained by modulating the interaction between stages of visual orienting and cue-target correlation, where the two similar tendencies (both interference and facilitation) amplify the total distractor effect while the two opposite tendencies tend to annihilate each other. Fig. 5A illustrates the results by Gusev et al. (2010). In Fig. 5B, the same result is depicted in the form of the DP. Again, this result can be explained by modulating the interaction between the stages of visual orienting (sensory level) and the cue-target correlation (correlation level). Here, the two similar tendencies (both interferences or both facilitations) amplify the total distractor effect while the two opposite tendencies tend to annihilate each other. This explanation is illustrated in Fig. 5C.

Finally, there is further evidence that the correlation distractor effects may modulate those of the structural level. In several studies, the proportion of congruent and incongruent color-word Stroop stimuli was manipulated (Lindsay & Jacoby, 1991; Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982; Utochkin & Bolshakova, 2010). It was found that a magnitude of the distractor effect in the incongruent condition depended on this proportion manipulation. It might vary from severe interference in a low probability of incongruent trials to a relatively slight interference (Lowe & Mitterer, 1982), null effect (Utochkin & Bolshakova, 2010) or even a redundancy effect (Logan & Zbrodoff, 1979) in a high probability of incongruent trials.

8. Conclusion

In this section, I shall summarize the principal points of the formal distractor theory introduced in this present paper, as well as discussing some challenges that the present theory confronts.

The theory is based on the empirical assertion that any irrelevant stimulus, feature, item or event may affect task performance in two opposite ways, depending on particular conditions. These two ways are the interference effect and the redundancy effect. The null effect is considered as an intermediate state of the Interference-Redundancy dimension. Both interference and redundancy effects may originate from three domains: (1) sensory input, (2) structural units of perception and memory and (3) correlation between target and distractor. The General Rule of the theory predicts that the addition of distractors should elicit interference through increased entropy. On the other hand, it predicts redundancy effects when an additional distractor is positively related to the critical target properties (which provides partial 'data compression' and target information weight increment). Furthermore, single or dual sets of processes may underlie the distractor effects. According to the single-process account, both interference and redundancy effects result from the same processes applied to certain segments of the processed dimension. From the dual-process viewpoint, there are two independent sets of processes; I-processes and R-processes, which operate the distractor in two different ways. I- and R-processes may partially share some sections of the distractor dimension. In this case, the overall distractor effect on performance depends on the I to R magnitude ratio. Distractor profiles (DPs) were introduced for the formalization and visualization of experimental results obtained in different studies in accordance with the formal theory. Finally, the hierarchical hypothesis and the evidence for it were discussed. It implies that the three sources of distractor effects may modulate others as subordinate and superordinate levels.

However, there are several important issues which are considered to be challenges for the formal distractor theory. The two of them are associated with the single- vs dual-process frameworks distinction. As was mentioned above, there are no formal criteria which provide an unambiguous choice between these two explanations in each particular case. The second problem is that there is no unitary algorithm to dissociate the I- and R-processes in the dual-process model. However, several ideas found in some experiments (e.g., Danziger &

Kingstone, 1999; MacLeod, 1998) may serve as potential candidates for the developing such a procedure. The third issue is associated with the formal prediction about the distractor. As soon as the General Rule of the theory is formulated in terms of entropy and redundancy, it is useful to have indices to measure both. This will allow strict predictions whether or not the distractor is 'positive' or 'negative' in relation to the current target. Of course, Shannon's mathematical theory of communication already included the mathematical formulas for both entropy and redundancy (Shannon, 1948). However, the formulas which are based on probabilities are well formalized for natural languages rather than for distractor-target interactions. They may be easily applied to some paradigms such as the Reicher-Wheeler task (since it appeals to lexical associations) or the Garner task (where probabilistic parameters are manipulated directly). But it is far more difficult to compute the theoretical entropy or redundancy due to the perceptual similarity in search tasks and especially due to SOAs manipulations in cueing, priming or serial masking procedures. The theoretical elaboration of these issues as well as further empirical tests of the hierarchical hypothesis may be considered to be the most important steps in developing the present theory.

9. Acknowledgements

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