

Attentional Switching in Spatial and Nonspatial Domains: Evidence From the Attentional Blink

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Much is known about attentional switching across space, but much less about switches between nonspatial domains such as category or task. Nonetheless, extensive information about attentional switching in both spatial and nonspatial domains can be found in the experimental literature on a phenomenon known as the *attentional blink*, in which a switch is required between 2 rapidly sequential targets. If the 2 targets follow one another directly, identification of the second target is almost perfect when no attentional switch is required between the targets or when the switch is unidimensional. In contrast, identification is impaired with switches in location or with multidimensional switches. This pattern of results is consistent with the joint operation of location-specific endogenously controlled input filters and exogenously controlled domain-specific modules.

Attentional Switching in Spatial and Nonspatial Domains

Attention can be distributed across space or among nonspatial stimulus attributes such as color, shape, or category. Distribution of attention across space has been studied extensively (see reviews by Kinchla, 1992, & LaBerge, 1990). A major objective of those studies was to discover the rules that govern how quickly, how accurately, and under what conditions the focus of attention can be switched to different regions in space. In contrast, as was pointed out by Allport, Styles, and Hsieh (1994), the study of attentional set in domains other than spatial has been aimed principally at discovering how well a given set can be maintained in the presence of interfering stimuli. Well-known examples are studies of the Stroop effect (reviewed by MacLeod, 1991) and of dual-task interference (reviewed by Pashler, 1998, especially chapter 6). Considerably less work has been done on the dynamics of *switching* attentional set in nonspatial domains.

In studying the dynamics of attentional switching, whether in spatial or nonspatial domains, the main issue is how the cognitive system reconfigures itself to cope with rapidly changing demands

of stimulus processing, response planning, or both. The main questions are how quickly this can be done, and what variables influence the resetting. Some of these questions have been addressed in recent studies involving attentional switching in domains other than spatial. For example, Allport et al. (1994) studied the temporal course of attentional switching in tasks that required rapid changes from physical to semantic attributes of the stimuli and involved different cognitive operations and response modes. In a similar vein, Rogers and Monsell (1995) studied the dynamics of task-set reconfiguration by requiring participants to switch repeatedly between a digit task (even/odd classification) and a letter task (consonant/vowel classification). Meiran (1996) studied how the temporal interval between a leading cue and a trailing target influenced the ease of task switching. Despite these and similar studies (see also Monsell, 1996), Allport et al. (1994) pointedly noted that data on the dynamics of attentional switching in domains other than spatial remain relatively scarce.

To be sure, an inspection of the literature does reveal a dearth of studies explicitly aimed at attentional switching in nonspatial domains. By the same token, inspection of the literature also reveals a wealth of information about nonspatial attentional switching in studies not explicitly designed for that purpose. Much of that information has been gathered in studies of a phenomenon known as the *attentional blink* (AB). More precisely, the salient information comes from a specific detail of the attentional blink, known as *Lag-1 sparing*. Although the relationship between the attentional blink and attentional switching is not immediately obvious, closer inspection of the literature reveals a massive amount of information that bears directly on the issue of attentional switching, both in the spatial and nonspatial domains. Before reviewing those findings, we provide a thumbnail sketch of the attentional blink and of Lag-1 sparing.

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The Attentional Blink and Lag-1 Sparing

Rapid visual sequences, like those generated from a series of eye movements or from changing views of an object in motion, can tax the limited processing capabilities of the visual system. If the system becomes overloaded, stimuli in the input stream may fail to be fully processed. The cost of such overloading can be seen in a transitory processing deficit, known as AB, in which the second of two targets fails to be identified if it is presented shortly after the first. Several procedures have been used to study the AB deficit. Perhaps the most common is known as rapid serial visual presentation (RSVP), in which the two targets are inserted in a stream of distractors, with all items presented in the same location. Items are displayed at a rate of one every 100 ms or so, each target being masked by the next item in the stream. If the two targets are displayed within a critical temporal interval, identification is nearly perfect for the first but is substantially reduced for the second. The robustness of this second-target deficit has been confirmed in a number of psychophysical and electrophysiological investigations (Chun & Potter, 1995; Duncan, Ward, & Shapiro, 1994; Luck, Vogel, & Shapiro, 1996; Raymond, Shapiro, & Arnell, 1992).

Resource limitations have been singled out as likely contributing factors in the AB (e.g., Chun & Potter, 1995; Duncan et al., 1994; Shapiro, Raymond, & Arnell, 1994). The second-target deficit is said to occur because processing resources that are required in common by the two targets are not available (or are less available) for dealing with the second target until processing of the first target has been completed. On this account, the deficit should be at a maximum when the second target is presented directly after the first, namely, when it is presented in the ordinal display position known as Lag 1. The deficit should then diminish as the lag is increased, reflecting the increasing availability of resources

that can be deployed to the second target as processing of the first target nears completion.

Precisely such a monotonic trend over lags has been found in many of the experiments reviewed below. Monotonic trends, however, are far from being the rule. A number of other studies, beginning with Raymond et al.'s (1992) original demonstration of the AB, have revealed U-shaped trends over lags, with the deficit being most pronounced not at Lag 1 but at Lags 2 or 3, that is, when the second target lagged the first by 200–300 ms (e.g., Chun & Potter, 1995; Giesbrecht & Di Lollo, 1998; Shapiro et al., 1994). In these experiments, performance was virtually unimpaired at Lag 1, but dropped dramatically at Lags 2 and 3 before recovering at longer lags. Here, we follow Potter, Chun, Banks, and Muckenhaupt's (1998) practice of referring to this effect as Lag-1 sparing. Examples of Lag-1 sparing and of total absence of Lag-1 sparing are illustrated in Figures 1A and 1B, respectively.

Lag-1 Sparing and Attentional Switching

Lag-1 sparing has been ascribed to the sluggish closing of an attentional gate (Chun & Potter, 1995; Shapiro & Raymond, 1994). The gate is said to open rapidly on presentation of the first target (T1) but to close sluggishly, thus allowing the next item in the stream (i.e., the Lag-1 item) to gain access to processing resources along with T1. If the trailing item happens to be the second target (T2), both targets are processed together, and the AB deficit is avoided. The notion of a sluggish attentional gate is akin to Sperling and Weichselgartner's (1995) concept of a discrete attentional episode, or an attentional window, which takes at least 150–200 ms to close. In Sperling and Weichselgartner's analogy, Lag-1 sparing occurs when both targets enter the same attentional window and are, therefore, part of the same attentional episode.

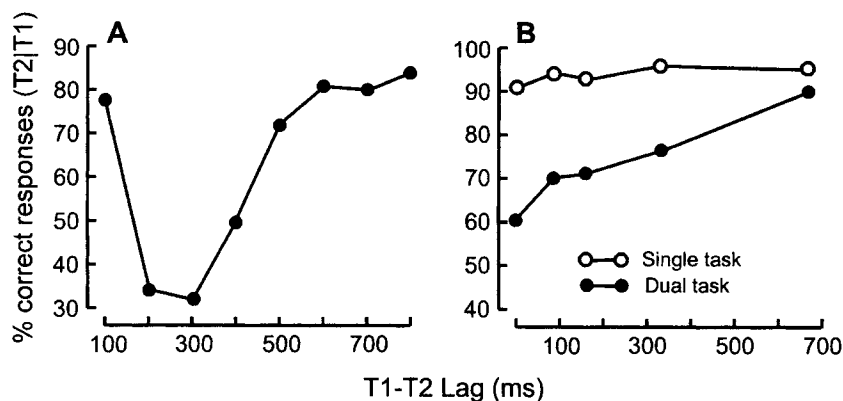


Figure 1. Panel A: Percentage of correct identifications of the second target as a function of the temporal lag from the onset of the first target to the onset of the second. Performance at the shortest lag exhibits Lag-1 sparing. (From "A Two-Stage Model for Multiple Target Detection in Rapid Serial Visual Presentation" by M. M. Chun and M. C. Potter, 1995, *Journal of Experimental Psychology: Human Perception and Performance*, 21, p. 112, Figure 2. Copyright 1995 by the American Psychological Association. Adapted with permission of the authors). Panel B (filled symbols): As for Panel A, except that performance at the shortest lag does not exhibit Lag-1 sparing. The open symbols represent performance on the second target when it was the only target in the display sequence. This is a frequently used control condition. T1 = target 1; T2 = target 2. (From "Attentional Requirements in a Preattentive Feature Search Task" by J. S. Joseph, M. M. Chun, and K. Nakayama, June 19, 1997, *Nature*, 387, p. 806, Figure 2. Copyright 1997 by Macmillan Publishers Ltd. Adapted with permission.)

Attentional gating has been used as an explanatory principle in studies that yielded evidence of Lag-1 sparing. On the other hand, absence of Lag-1 sparing has seldom attracted comment (but see Potter et al., 1998). This theoretical neglect would be understandable if the absence of Lag-1 sparing were an infrequent event, attributable to chance. But, it is not. To anticipate an outcome of the present review, Lag-1 sparing was obtained in approximately half the experiments reported in the literature but failed to be obtained in the other half. This prompts an obvious question. Assuming that Lag-1 sparing occurs because T2 enters the same attentional window as T1, why is it that it can do so in one half of the experiments but not in the other half? An account in terms of temporal contiguity alone is clearly insufficient. Other factors must also be at work.

Failure of Lag-1 sparing does not necessarily disconfirm an attentional-gating account. Rather, it suggests that two sequential stimuli can become part of the same attentional episode under some conditions but not under others. The task, then, is to uncover and classify the factors that determine whether sequential stimuli give rise to the same or to different attentional episodes. From this perspective, Lag-1 sparing ceases to be a phenomenon confined strictly to the AB deficit and becomes salient to attentional issues of far greater scope. We believe it to be especially relevant to issues relating to the distribution of attention and to rapid changes in attentional set in both spatial and nonspatial domains.

In studies of the AB, the observer must perform an attentional switch from T1 to T2 across a brief temporal lag. For this reason, studies of the AB can provide information relevant to the dynamics of switching attentional sets. To be sure, the precise form of the attentional switch in any given AB study was incidental to the main purpose of the investigation. Nevertheless, performance at Lag 1 provides an index of how rapidly and how well the system can reconfigure itself to cope with the changing demands of processing the second target when it is presented directly after the first. Presence of Lag-1 sparing suggests that an attentional switch from T1 to T2 could be performed successfully, with little consequence for the accuracy of T2 identification. Absence of Lag-1 sparing, on the other hand, suggests that an attentional switch could not be performed successfully, perhaps because the nature of the switch placed greater demands on the process of system reconfiguration, and performance on T2 suffered accordingly. On this reasoning, by identifying the factors that influence the occurrence of Lag-1 sparing, we would also be identifying factors relevant to switches in attentional set.

To this end, we undertook a systematic examination of the experimental evidence on Lag-1 sparing. This consists largely of studies of the AB published since Raymond et al.'s initial report in 1992. Among these studies, we counted over 100 separate experimental conditions that revealed significant AB deficits and that, therefore, provided pertinent information on the conditions relating to Lag-1 sparing.

A wide variety of attentional switches between T1 and T2 have been implemented in AB studies. As a first step, we devised a taxonomic scheme based on a four-fold classification: switches in location, modality (visual/auditory), task (e.g., identify/detect), or category (e.g., digit/letter). This scheme emerged from an initial survey of the experimental literature and is described further below, along with the choice of a criterion for distinguishing between presence and absence of Lag-1 sparing.

Method

Inclusion Criteria

The data for the survey were obtained almost entirely from studies of the AB, provided that two conditions were met.

1. A significant AB deficit had to be present in the experimental condition under consideration. Clearly, a lag-dependent trend in performance, as in the AB deficit, is a prerequisite for assessing the presence or absence of Lag-1 sparing. This criterion rules out instances such as Potter et al.'s (1998) Experiment 3, in which no AB deficit was found following unidimensional cross-modal switches. The individual studies included in the data base are listed in Table 1.

2. The experimental design had to allow T2 to be presented at the Lag-1 position in the display sequence. In conventional AB experiments, this corresponds to a stimulus-onset asynchrony (SOA) of about 100 ms between the onsets of T1 and T2. Clearly, unless T2 can appear in the Lag-1 position, no assessment of Lag-1 sparing can be made. This criterion also rules out instances in which the item in Lag 1 was explicitly omitted, as was the case for three of the four conditions in Experiment 3 by Raymond et al. (1992). This criterion also rules out instances in which the SOA between T1 and T2 was substantially longer than 100 ms, as was the case in the studies by Ward, Duncan, and Shapiro (1997, Experiment 1) and Broadbent and Broadbent (1987, Experiment 3).

Definition of Lag-1 Sparing

A first requirement of the present work was the specification of a criterion for defining the occurrence of Lag-1 sparing. At one extreme, Lag-1 sparing can be said to be clearly present if the level of performance at Lag 1 is substantially higher than that at the next few lags, as illustrated in Figure 1a. At the other extreme, Lag-1 sparing can be said to be clearly absent if performance at Lag 1 is below the lowest level at the next few lags, as illustrated in Figure 1b. In some studies, the lowest level to which performance could drop was constrained by the floor of the response scale. This constraint might have produced spurious evidence of Lag-1 sparing by preventing performance at Lag 1 from dropping to a level lower than that of the next few lags. Mainly for this reason, we adopted a conservative criterion. Lag-1 sparing was said to have occurred if the level of performance at Lag 1 exceeded the lowest level of performance by more than 5% in absolute terms, namely, 5% of the correct responses represented on the y-axis of the published graph. We estimated level of performance at any given lag by projecting the relevant points in the curve onto the y-axis of the published graphs.

Taxonomic Scheme

A fundamental requirement of the present work was to develop a scheme for classifying the types of switches that were implemented between T1 and T2 in the studies reported in the literature. To this end, we examined the studies in the database for all salient differences between T1 and T2. These included, but were not limited to, differences in the categorical identity of the targets (e.g., letters vs. digits), the target attribute(s) to which the observers were required to respond, the spatial locations in which the targets were displayed, the sensory modality in which they were presented, various physical attributes such as color and brightness, and the type of response(s) made by the observers. This resulted in a list of items, each representing some kind of switch between T1 and T2. We found that the items in the list could be clustered in four classes: switches in location, modality, task, and category, as explained below.

Location switches. These included switches above and below a central fixation point (Allport et al., 1994) and switches between T1 in a central location and T2 in a more peripheral location (Joseph, Chun, & Nakayama, 1997).

Modality switches. These included both auditory T1 and visual T2, and vice versa (Arnell & Jolicoeur, 1998; Potter et al., 1998).

Task switches. These were switches in the type of response that the observers were required to make to T1 and T2. Almost invariably, the switch was between identification of T1 and detection of T2, which is not surprising because this was the task switch used in Raymond et al.'s (1992) original AB experiments. Far less frequently, task switches involved classification of digits as being even or odd, or a lexical decision (Luck et al., 1996).

Category switches. In most cases, these were switches between digits and letters. There were also switches between geometrical patterns and letters (Chun & Potter, 1995; Joseph et al., 1997), color of the items (Chun, 1997), voice pitch of spoken items (Duncan, Martens, & Ward, 1997), and between auditory tones and letters (Arnell & Jolicoeur, 1998). In one case, category switches were between items denoting animals, nonanimals, or objects smaller than a soccer ball (Allport et al., 1994). The wide variability of category switches implemented in individual experiments need not be of major concern. The results indicate that, when these category switches were implemented singly, Lag-1 sparing was virtually as strong as when there were no switches.

Results

The results of the survey are presented in Table 1, which contains a total of 111 separate cases. A condensed summary is presented in Table 2. The major trends can be characterized as follows. Lag-1 sparing occurs reliably when there are no switches in attentional set between T1 and T2 or when the switch involves either task alone or category alone, provided that there are no other concomitant switches. Lag-1 sparing is not found with switches in location alone or with concurrent switches involving two or more of the four classes (location, task, category, or modality).

We now examine the incidence of Lag-1 sparing in relation to specific switches or combination of switches and note any exceptions to the overall trends. In Table 1, the entries in the column headed *Cond* refer to the number of conditions in each experiment that were included in the database. The entries in the columns headed *Lg-1 Sp* refer to the number of conditions in which Lag-1 sparing was (Yes) or was not (No) obtained.

No Switching

There were 46 separate experimental conditions with no switches between the targets. Of these, 44 revealed Lag-1 sparing, and 2 did not. One of the two exceptions, reported by Maki, Frigen, and Paulson (1997), showed a small amount of Lag-1 sparing that failed to exceed the 5% criterion. The other was reported by Maki, Couture, Frigen, and Lien (1997), who noted the absence of Lag-1 sparing but offered no account for it. It can be concluded that Lag-1 sparing occurs when the two targets belong to the same category, are presented in the same modality and in the same location, and the observer makes the same type of response to both.

Location Switching

Of 16 cases in which the two targets were displayed in different spatial locations, none revealed Lag-1 sparing. This result was true whether the spatial switch was implemented singly, as in the 16 cases mentioned above, or in conjunction with switches in one or more of the other three classes, as was done in 11 additional cases.

We conclude that Lag-1 sparing is not found following a switch in spatial location.

Task Switching

The data in Table 2 show 12 cases of simple task switching, mostly involving a switch from identifying T1 to detecting T2. Of the 12 cases, 9 revealed Lag-1 sparing, and 3 did not. Two of the exceptions were reported by Arnell and Jolicoeur (1998). It is interesting to note that, in both cases, the experiment involved the concurrent presentation of auditory and visual streams. The two targets were inserted among distractors in the to-be-attended modality stream, whereas only distractors were presented in the to-be-ignored modality stream. It is conceivable that the observers may have found it difficult to ignore totally the irrelevant stream. If so, the resulting division of attention would bear some similarity to cases of concurrent attentional switching, discussed below, in which Lag-1 sparing is reliably missing. The third exception, reported by Shapiro et al. (1994, Experiment 1), revealed a small amount of Lag-1 sparing, which did not exceed the 5% criterion level.

Category Switching

Only five cases of category switching without other concomitant switches are listed in Table 2. Of these, four revealed Lag-1 sparing, and one did not. It is interesting to note that the single exception (Duncan et al., 1997, Experiment 2) involved the concurrent presentation of distractors in the to-be-ignored modality stream, as in the above-mentioned study by Arnell and Jolicoeur (1998). This is in agreement with the suggestion that divided attention may reduce or eliminate Lag-1 sparing.

Modality Switching

When the two targets are presented in different modalities, an AB deficit is never found unless there are concomitant switches in other dimensions (e.g., Potter et al., 1998). Because the presence of an AB deficit was a criterion for inclusion in the database, it follows that there were no instances of Lag-1 sparing with simple modality switches. It would be premature, however, to conclude that modality switches are irrelevant. As noted below, they have a strong effect when implemented in conjunction with other switches.

Multiple Switching

As seen in the lower half of Table 2, there were 32 cases in which concurrent switches were implemented in more than one dimension. Of these, 3 revealed Lag-1 sparing, and 29 did not. It seems clear that, in the bulk of the cases, multidimensional switches lead to an absence of Lag-1 sparing. The synergy of concurrent switches in preventing Lag-1 sparing should be noted. When implemented alone, switches in task or category yielded Lag-1 sparing in 76% of the cases. Yet, when the two switches were implemented concurrently, Lag-1 sparing was found in only 18% of the cases. This synergistic effect applies also to modality switches that, when implemented alone, never produce an AB deficit, much less Lag-1 sparing. Yet, when modality switches are

Table 1
Types of Switches in Attentional Set and Occurrences of Lag-1 Sparing in the AB Literature

Study	Cond	Switch type				Lg-1 Sp.	
		Loc	Mod	Task	Cat	Yes	No
Allport et al. (1994)							
Expt. 6	2	2			2		2
Expt. 7	2	2					2
Arnell & Duncan (1997)							
Expt. 1	1		1		1		1
Expt. 2	1	1			1		1
Arnell & Jolicoeur (1998)							
Expt. 1	4		2	4			4
Expt. 2	4		2	4	4		4
Expt. 3	2		2	2	2		2
Expt. 4	1		1	1	1	1	
Expt. 5	6			6	6		6
Broadbent & Broadbent (1987)							
Expt. 1	1					1	
Expt. 2	2					2	
Chun (1997)							
Expt. 1	1					1	
Chun & Potter (1995)							
Expt. 1	1					1	
Expt. 2	2					2	
Expt. 3	2					2	
Expt. 4	4					4	
Expt. 5	3					3	
Expt. 6	2					2	
Expt. 7	1					1	
Duncan et al. (1997)							
Expt. 1	1				1		1
Expt. 2	1	1					1
Duncan et al. (1994)							
Expt. 1	1	1			2		1
Expt. 2	1	1					1
Breitmeyer et al. (in press)							
Expt. 1	3	2				1	2
Expt. 2	4	4					4
Expt. 3	4	4					4
Expt. 4	2					2	
Giesbrecht & Di Lollo (1998)							
Expt. 1	2					2	
Expt. 2	2					2	
Expt. 3	3					3	
Joseph et al. (1997)							
Expt. 1	1	1		1	1		1
Expt. 2	2	2		2	2		2
Luck et al. (1996)							
Expt. 1	1			1	2	1	
Maki, Couture, et al. (1997)							
Expt. 1	2					2	
Maki, Frigen, et al. (1997)							
Expt. 1	2					2	
Expt. 2	2						2
Expt. 3	3					3	
Moore et al. (1996)							
Expt. 1	2	2			2		2
Expt. 2	2	2			2		2
Peterson & Juola (1997)							
Expt. 2	4	2				2	2
Potter et al. (1998)							
Expt. 1	1					1	
Expt. 2	1					1	
Expt. 4	4		2	4	4	1	3
Expt. 5	1					1	
Raymond et al. (1992)							
Expt. 2	1			1		1	

Table 1 (continued)

Study	Cond	Switch type			Cat	Lg-1 Sp.	
		Loc	Mod	Task		Yes	No
Expt. 3 Seiffert & Di Lollo (1997)	1			1		1	
Expt. 1 Shapiro et al. (1997)	1			1		1	
Expt. 1	1			1		1	
Expt. 2	3			3		3	
Expt. 3	2			2		2	
Expt. 1 Shapiro et al. (1994)	1			1			1
Expt. 2	1					1	
Expt. 3a	1					1	
Expt. 3b	1					1	
Expt. 4	1				1	1	
Expt. 1 Vogel et al. (1998)	2				2	2	
Expt. 2	1				1	1	

Note. Cond = number of conditions; Loc = location switch; Mod = modality switch; Task = task switch; Cat = category switch; Lg-1 Sp. = Lag-1 sparing; Expt. = experiment.

implemented in conjunction with switches in task, category, or both, Lag-1 sparing is reliably missing.

Special mention must be made of an experiment by Ward et al. (1997, Experiment 2), which met the criteria for inclusion in the multiple-switch classification but was excluded from the present analysis because the results were ambiguous in respect to Lag-1 sparing. When grouped on the basis of stimulus category, Lag-1 sparing was in evidence, in at least two of the three categories (Ward et al., 1997, Figure 3). Yet, when grouped on the basis of stimulus size, there was no evidence of Lag-1 sparing. This pattern of results is intriguing and potentially important. However, the details provided in the published report are insufficient for an informed hypothesis to be formulated. Therefore, the results of that experiment were omitted from the present analysis.

Discussion

Allowing for very few exceptions, the results of the survey can be summarized as follows. Lag-1 sparing is found when no switches in attentional set are implemented between the targets or when the switch is unidimensional, involving a change in either task or category. Lag-1 sparing is not found with switches in location or with concurrent switches involving two or more dimensions.

Lag-1 Sparing and Attentional Gating

This pattern of results can be readily explained by a revised version of the attentional-gating model outlined in the Introduction. According to that model (Chun & Potter, 1995; Shapiro & Raymond, 1994), Lag-1 sparing occurs when T1 and T2 occupy the same attentional window. That window is said to open at the onset of T1 and to close some 150–200 ms later. If T2 enters the window, the two targets become part of the same attentional episode, and both gain access to processing mechanisms required

for stimulus identification and response planning. A central tenet of this model is that access to the attentional window is predicated exclusively on temporal contiguity. Provided that T2 (or, for that matter, any other stimulus in the input stream) arrives within a critical period after T1, it will enter the same attentional window.

This cannot be true in precisely the form stated in the model. If temporal contiguity were the only criterion for entering the same window, then Lag-1 sparing would always take place, provided that the intertarget interval is less than the duration of the temporal window. Given that the critical interval was approximately the same in all experiments listed in Table 2, the model cannot explain why Lag-1 sparing was not found in about half the cases. To account for the data, the model is in need of an additional criterion, besides temporal contiguity, by which to predict whether or not two successive targets will enter the same window. We propose such a criterion in the form of a filter that controls access to the

Table 2
Incidence of Lag-1 Sparing by Switch Type(s)

Type of switch	Lag-1 sparing	
	Yes	No
None	41	2
Loc	0	16
Task	9	3
Mod	0	0
Cat	4	1
Loc, Cat	0	8
Task, Cat	2	9
Mod, Task	0	2
Mod, Cat	0	1
Mod, Task, Cat	1	6
Loc, Task, Cat	0	3

Note. Loc = location; Mod = modality; Cat = category.

attentional window. The characteristics of the filter are suggested by the data in Table 2.

As can be seen in Table 2, there is a relationship between Lag-1 sparing and the type of attentional switch implemented between the two targets. At one extreme, Lag-1 sparing is found reliably when there is no switch in attentional set. At the other extreme, Lag-1 sparing is seldom found when there is a substantial switch involving concurrent changes in two or more dimensions. Cast in the language of the model, these findings suggest that the two targets can enter the same window when their processing requirements are similar but not when they differ substantially.

This is tantamount to saying that to enter the attentional window, incoming stimuli must pass through an input filter that is set to pass the targets but to exclude all nontarget items. Given the temporal sequence in the input stream, the filter is initially set to allow entry for T1. For example, the filter may be set to identify an uppercase letter while excluding digits and other symbols. The data in Table 2 reveal one further characteristic of the input filter. Lag-1 sparing is never found following a switch in location, whether implemented alone or in conjunction with a switch in another dimension. This suggests that the filter and the corresponding attentional window are tied to a specific location in space, as was hypothesized by Sperling and Weichselgartner (1995).

It is important to distinguish between the locational specificity of the filter and its spatial extent. It is known that the spatial extent of attention can vary substantially, depending on task demands. Attention can be focused narrowly within a small spatial area or broadly over a large area containing several objects (Eriksen, Pan, & Botella, 1993). Thus, Lag-1 sparing is absent when a task requires an attentional switch from an attended location to an area outside the focus of attention. In this case, the input filter must be repositioned from one location to another. In contrast, a corresponding deficit does not occur when a task requires the identification of multiple stimuli within a larger attended area, as was done in Sperling's (1960) seminal experiments on iconic memory. In this case, no repositioning of the input filter is required.

There is a clear suggestion in Table 2 that an incoming stimulus need not match the input filter perfectly to gain access to the attentional window. In experiments in which T1 and T2 differed along a single dimension (task or category), Lag-1 sparing was highly probable. The effect was found in 13 of 17 instances, and, as was noted earlier, in three of the four exceptions the switches could be considered as multidimensional and, therefore, consistent with the absence of Lag-1 sparing. The fact that Lag-1 sparing occurs with unidimensional switches suggests that the input filter can be configured to fit both targets, provided that they are presented in the same locations and that they differ only along a single dimension.

In the revised model, T2 must meet two conditions to enter the same attentional window as T1: It must arrive while the window is still open (i.e., within 150–200 ms from T1), and it must match the characteristics of the input filter, including its spatial location. If these conditions are met, the two targets will become part of the same attentional episode, thus obviating the need for attentional switching between them.

Input filters serving much the same purpose as those discussed above have been proposed in studies of the AB and in studies of visual search. Shapiro and Raymond (1994) have advanced the notion of an input filter in the form of a template which controls

access to short-term visual memory in studies of the AB. The idea is that, before gaining entry into the memory store, incoming items are matched against internal templates of the targets. If the similarity between item and template is low, as would be the case for nontargets, the item is excluded from short-term visual memory. Equivalent filtering operations have been proposed by Duncan and Humphreys (1989) to account for similarity effects in visual search and by Yantis and Johnston (1990) to reconcile early- and late-selection accounts of visual attention.

Filtering need not be restricted solely to physical features. Rather, the reconfiguring of a filter is probably part of a more comprehensive and goal-oriented process aimed at selecting those stimulus attributes and characteristics that are likely to prove useful for performing the task at hand. Monsell (1996) has referred to a similar process as *task-set reconfiguration*. In Monsell's view, this is "... a process of enabling and disabling connections between processing modules and/or re-tuning the input-output mappings performed by these processes, so that the same type of input can be processed in the different way required by the new task." (Monsell, 1996, p. 135).

In summary, the bulk of the data on Lag-1 sparing supports a revised version of the attentional-gating model in which entry into a single attentional window is predicated not only on the temporal contiguity between T1 and T2 but also on the similarity of their processing requirements. Given temporal contiguity, the greater that similarity, the greater the probability of both targets being processed together. Next, we consider the relationship between Lag-1 sparing and the AB deficit, and what happens if T2 fails to enter the same window as T1.

Lag-1 Sparing and the AB Deficit

Should Lag-1 sparing and the AB deficit be regarded as independent events or as different expressions of the same phenomenon? To anticipate, the empirical evidence is substantially in favor of independence, but the theoretical underpinning is scant. Current models offer only limited help on this issue because theoretical development has focused almost entirely on the AB deficit alone. It is fair to say that Lag-1 sparing has been treated with the theoretical equivalent of benign neglect. When mention is made of Lag-1 sparing, it is usually to ascribe it to a sluggish attentional gate and to say no more about it.

Not so for the AB deficit. In a recent synopsis, Shapiro, Arnell, and Raymond (1997) identified five separate theoretical accounts: The model of Shapiro and colleagues, in which the AB is said to stem from interference in a short-term storage buffer (Shapiro et al., 1994), a model in which the AB deficit represents the dwell time of attention (Duncan et al., 1994), a two-stage model in which T2 becomes degraded in one processing stage while T1 is being processed in the other (Chun & Potter, 1995), an object-substitution account in which T2 is said to be replaced in consciousness by the trailing mask (Giesbrecht & Di Lollo, 1998), and a model in which the AB is viewed as an instance of a broader class of events known as the psychological refractory period (Jolicoeur, 1998). We concur with Shapiro et al.'s (1997) opinion that these models share broad characteristics and are in many respects equivalent.

Among these broadly corresponding models, Chun and Potter's (1995) two-stage formulation readily lends itself to a comparison

between Lag-1 sparing and the AB deficit. Here is a brief outline of it, supplemented by elements of the other models. The basic structure of the model consists of two sequential processing stages. In Stage 1, potential targets are selected on the basis of physical features, configuration, or category (e.g., digits vs. letters). Items designated as potential targets gain access to Stage 2, where further processing takes place, culminating in the response. Processing in Stage 2 is held to be serial and to be constrained by capacity limitations. An important postulate is that stimuli can enter Stage 2 only if it is not busy. Thus, if T2 arrives while Stage 2 is busy with T1, it is delayed in Stage 1 until Stage 2 is free. During the period of delay, T2 is vulnerable to masking by a subsequent stimulus. If such a mask arrives while T2 is still in Stage 1, a process of substitution takes place in which the representation of T2 is replaced by that of the mask. In this event, an AB deficit occurs because it is the mask, not T2, that eventually gains access to the processing mechanisms in Stage 2.

Within this conceptual framework, Lag-1 sparing can be explained on the basis of processing events in Stage 1. The input filters discussed in the previous section are identifiable with the selective mechanisms in Stage 1 or, equivalently, with the peripheral templates postulated by Shapiro and Raymond (1994). The present work supplements these earlier formulations by analyzing the characteristics of the filters and by specifying the conditions under which incoming stimuli, notably T2, may gain access to Stage 2. On this basis, T1 and T2 will gain joint access to Stage 2 if they meet the filter's specifications. These are that both stimuli be presented at the same location, that their temporal separation not exceed the duration of the temporal window, and that the differences in their processing demands not require a major switch in attentional set. If these conditions are met, T2 will gain immediate access to Stage 2, thus escaping masking by the trailing item. In this event, Lag-1 sparing ensues. If T2 does not pass the initial filter, perhaps because it is presented at a different location than T1, or because it differs from T1 in more than one dimension, an appropriate new filter needs to be set up (cf. Sperling & Weichselgartner, 1995). By the time the new filter is ready, the temporal window will have closed, and T2 will remain in Stage 1, vulnerable to masking until Stage 2 is again free. In this event, Lag-1 sparing does not occur.

We are led by this analysis to conclude that Lag-1 sparing and the AB deficit are distinct phenomena, separable on a number of dimensions. Lag-1 sparing arises from the action of input filters that have relatively brief temporal constants and are tied to specific spatial locations. The filters are dynamically reconfigured in accordance with rapid switches in attentional set. The AB deficit, on the other hand, arises from capacity limitations at processing levels where domain-specific modules deal with complex stimulus attributes and oversee response planning and execution. Such processing lasts considerably longer than processing at earlier stages. Electrophysiological recordings of brain responses, like the P300 and N400 waves, show evidence of AB-related activity over intervals as long as 700 ms after stimulus presentation (Luck et al., 1996; Vogel, Luck, & Shapiro, 1998).

Strong empirical support for the separability of Lag-1 sparing and the AB deficit has been reported by Peterson and Juola (1997, Experiment 2). Three separate RSVP streams (120 ms/item) were displayed concurrently at the vertices of an imaginary equilateral triangle on the perimeter of an imaginary circle of 1.4° diameter.

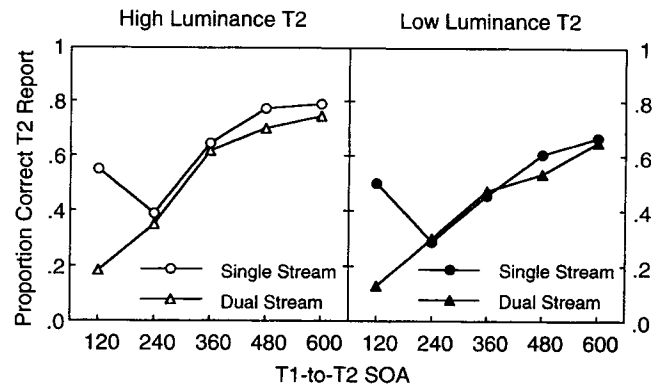


Figure 2. Proportion of correct identifications of the second target as a function of the temporal lag from the onset of the first target to the onset of the second. In the single-stream conditions, the two targets were presented in the same spatial locations; in the dual-stream conditions they were presented in different locations. Lag-1 sparing is exhibited in the single-stream but not in the dual-stream conditions, regardless of level of luminance. SOA = stimulus onset asynchrony; T1 = target 1; T2 = target 2. (From *Spatial and Temporal Dynamics of Attentional Gating and the Attentional Blink* by M. S. Peterson and J. F. Juola, November 1997, poster session presented at the 38th Annual Meeting of the Psychonomic Society, Philadelphia, Pennsylvania. Reprinted with permission.)

Observers were told that T1 and T2, which were both letters, would be presented either in the same stream (single-stream condition) or in different streams (dual-stream condition). At the beginning of each trial, appropriate cues indicated the stream(s) in which T1 and T2 were to be displayed. Observers were required to identify T1 and T2. On dual-stream trials, T1 also served as a signal to switch attention to the stream in which T2 was to be presented.

Illustrated in the two panels of Figure 2 are the results of Peterson and Juola's (1997) Experiment 2, obtained with different intensities of T2. The intensity manipulation is irrelevant for the present purpose, but it underscores the robustness and generality of the results of interest here. At both levels of luminance, the pattern of results reveals a decoupling between Lag-1 sparing and the AB deficit. The decoupling is revealed by the fact that the two phenomena respond in dramatically different ways to changes in the same variable, namely, a switch in spatial location. In both panels, the single-stream and dual-stream functions differ sharply at Lag 1, attesting to the critical importance of the location switch for Lag-1 sparing. Beyond Lag 1, however, the two functions are virtually indistinguishable from each other, indicating that the location switch had no effect on either the magnitude or the temporal course of the AB deficit. In addition, as was pointedly noted by Peterson and Juola, the two phenomena differ sharply in temporal extent. Whereas Lag-1 sparing is over within 200 ms or less, the AB deficit extends for durations of 500 ms and beyond.

Further evidence in favor of independence can be obtained by reanalyzing the results of those experiments in which Lag-1 sparing was found. If it is the case that Lag-1 sparing and the AB deficit are independent events, it should also be the case that their magnitudes should be unrelated to each other. To check on this relationship, we compared the magnitudes of Lag-1 sparing and the AB deficit in those studies in Table 1 in which Lag-1 sparing was found. We began by defining the following three variables:

1. Peak AB: the highest score minus the lowest score across all lags.

2. Magnitude of Lag-1 sparing: the score at Lag 1 minus the lowest score across all lags.

3. Normalized Lag-1 sparing: magnitude of Lag-1 sparing (b) divided by peak AB (a).

To avoid artifactual distortions in the distribution, we ignored all cases in which Lag-1 sparing was at ceiling, namely, all cases in which the magnitude of Lag-1 sparing was equal to the magnitude of the AB. The scattergram in Figure 3 was constructed by plotting the normalized Lag-1 sparing scores against the corresponding peak AB scores.

Separability of Lag-1 sparing and the AB in Figure 3 is indexed by two factors: the slope of Lag-1 sparing on AB and the variance of the Lag-1 sparing scores. If the magnitude of Lag-1 sparing were related to the magnitude of the AB, whether positively or negatively, that relationship should be evidenced by a significant correlation between the two variables. In Figure 3, this correlation would be evidenced by a clustering of points about the regression line. Separability would be indicated by a correlation of zero. There is one case, however, in which a correlation of zero may occur even if the two variables were related. If Lag-1 sparing and peak AB were related so that the magnitude of Lag-1 sparing was a fixed proportion of the peak AB, then the normalized Lag-1 sparing scores would be clustered around that fixed value at all AB magnitudes. In Figure 3, this cluster would be seen as a horizontal band of points across the domain. In this case, the hypothesis of independence would be testable not by the slope of the regression line, which would be zero, but by the variance of the points about that line. Namely, if Lag-1 sparing and peak AB were unrelated, the points should be distributed randomly across the entire surface of Figure 3.

On these considerations, we can state two null hypotheses, one with respect to the slope (H_{0s}), the other with respect to the variance (H_{0v}): H_{0s} : the slope of the regression line of Lag-1 sparing on AB is zero, and H_{0v} : the Lag-1 sparing scores are uniformly distributed in the interval [0, 1]. Under these null hypotheses, the slope should be zero, and the variance should be $1/12 = 0.083$, which is the variance of a random variable distributed uniformly in the interval [0, 1].

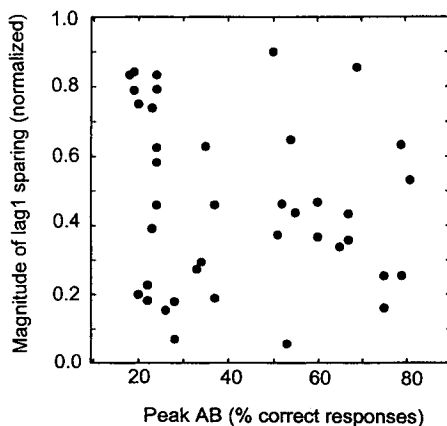


Figure 3. Scatter diagram of normalized Lag-1 sparing scores against peak attentional blink (AB) scores.

Empirical values calculated from the data were slope (empirical) = 0.00189 and variance (empirical) = 0.06000. To test the statistical significance of these values, we used a 2-tailed test with $\alpha = 0.05$. Rather than relying on classical statistical approximation theory (Stuart & Ord, 1991), we used bootstrap estimation techniques (Efron & Tibshirani, 1993; Foster & Bischof, 1991). Bootstrap estimates with 10,000 replications showed that, under the null hypotheses, the probability of obtaining a slope greater than the empirical slope was $P(\text{slope}_{\text{boot}} > \text{slope}_{\text{emp}}) = 0.8016$ (not significant), and the probability of obtaining a variance greater than the empirical variance was $P(\text{var}_{\text{boot}} > \text{var}_{\text{emp}}) = 0.9652$ (not significant). Neither null hypothesis can be rejected on the basis of this statistical analysis. Therefore, it can be tentatively concluded that Lag-1 sparing and the AB deficit are statistically independent.

To ensure that this conclusion was not specific to the peak AB measure, we replicated the statistical analysis with a different measure of AB magnitude. Instead of using peak AB, we estimated AB magnitude with the integration method used by Shapiro et al. (1994) and by Seiffert and Di Lollo (1997). For each lag, the mean percentage of correct responses was subtracted from 100, and the sum across lags was taken as the AB magnitude. The bootstrap analysis confirmed the hypothesis of independence of Lag-1 sparing and AB deficit: slope (empirical) = 0.00418, $P(\text{slope}_{\text{boot}} > \text{slope}_{\text{emp}}) = 0.8874$ (not significant); and variance (empirical) = 0.06840, $P(\text{var}_{\text{boot}} > \text{var}_{\text{emp}}) = 0.8918$ (not significant).

Independence of Lag-1 sparing and the AB deficit is precisely what would be expected if the two phenomena arose at different stages of processing and had distinct neurophysiological correlates. The temporal dynamics suggest that Lag-1 sparing arises early and that the AB deficit occurs later in the processing sequence. This suggestion is in line with the hypothesis that Lag-1 sparing may be based on the action of early filtering mechanisms, whereas the AB deficit may be based on the action of domain-specific modules that operate later in the chain of processing events.

Endogenous and Exogenous Control Functions

What emerges from the present review is a conception of endogenous and exogenous control functions that differs in important ways from the conventional outlook. Contrary to established views, the evidence marshaled in the present work points to a good deal of conceptually driven control at the input level and to a good deal of stimulus-driven control at higher processing levels.

Two sequential stages are usually postulated in theories of visual information processing (e.g., Neisser, 1967). The first is an input stage of virtually unlimited capacity in which the incoming stimuli are encoded in parallel. Importantly, processing at this stage is considered to be largely stimulus driven and hence under exogenous control. The second stage is concerned with higher-level processes and response programming. Its operations are said to be resource limited, serial, and governed by a unitary mechanism variously denoted as *supervisory attentional system* (Shallice, 1994), *controlled processing* (Shiffrin & Schneider, 1977), or *central executive* (Baddeley, 1986). In contrast to the earlier stage, processing at this later stage is considered to be conceptually driven and hence under endogenous control.

Contrary to these widely held views, the present evidence favors a reversal in the foci of exogenous and endogenous control. The

reasoning is as follows. In revising the attentional-gating account of Lag-1 sparing, we referred to input filters that are dynamically reconfigured under the control of signals from higher levels. It is the configuration of these filters that determines whether any given stimulus can gain access to domain-specific modules at higher processing levels. Because the filters are set by signals originating at higher brain centers, it follows that the functioning of the input stage must be governed in good part by endogenous, conceptually driven control signals.

Conversely, the second stage is governed, though indirectly, by exogenous stimulus-driven events. Suppose that a given stimulus, having passed through the input filters, has gained access to higher processing mechanisms where specialized feature-specific or task-specific modules are engaged. It is plausible to expect that the incoming stimulus will be appropriate for some of these domain-specific modules but not for others. What modules are activated by that particular stimulus will depend on the nature of the stimulus itself. For example, motion modules will be activated if the stimulus is in motion but not if it is stationary; similarly, color modules will be activated by chromatic but not by achromatic stimuli. It follows from these considerations that the functioning of domain-specific modules must be governed in good part by exogenous, stimulus-bound factors.

Neurophysiological Speculations

Implied in this viewpoint is a functional organization of the brain that differs sharply from that of a general-purpose central processor. Rather, our analogy is that of a number of independent yet interconnected special-purpose processors, operating in parallel on incoming signals that have passed through the filters at a lower level. This conception parallels the views expressed by Allport, Antonis, and Reynolds (1972), Allport et al. (1994), and Monsell (1996), among others, and is congruent with the modular organization of the visual system revealed in current neuroanatomical and neurophysiological studies (e.g., Felleman & Van Essen, 1991; Posner & Raichle, 1994). From the perspective of parsimony and efficiency, this scheme is eminently sensible because endogenous control of filtering operations permits a degree of selectivity of the input to higher processing levels. In this fashion, limited high-level processing resources can be devoted principally to stimuli that are relevant to the task at hand.

To function optimally as input gates, these filtering mechanisms need to operate at a relatively early stage of processing, when signals flowing toward higher cortical centers can be monitored. At the same time, the filters must be responsive to rapid changes in attentional set and in response planning, which are functions normally associated with high-level structures in prefrontal cortex (Goldman-Rakic, 1987, 1988). That the prefrontal cortex is intimately involved in the establishment and maintenance of attentional sets is confirmed by striking failures of selective attention in frontal lobe patients (Shallice, 1988).

Gating mechanisms may be located in many areas, depending on the nature of the attentional set. For example, attending selectively to stimuli in motion would probably include gating circuitry in cortical areas V1 and V5. However, there are strong indications that input filters can be set up even more peripherally than primary visual cortex. Among the likely candidates for subcortical gating mechanisms is the perigeniculate nucleus, which is a network

interposed between lateral geniculate nucleus and area V1. One of its important characteristics is that it receives direct excitatory input from prefrontal cortex (Skinner & Yingling, 1977; Steriade, Domich, & Oakson, 1986; Yingling & Skinner, 1977). Sitting astride the main input pathways to the visual cortex, the perigeniculate nucleus is ideally located for monitoring incoming sensory signals. In view of the linking neural circuitry, the hypothesis is almost compelling that attentional sets arising within prefrontal cortex become instantiated as input filters at lower levels in the visual system, as peripherally as the perigeniculate nucleus.

This is not to say that stimulus selection can be performed reliably, or even usually, within peripheral levels in the visual system. Indeed, there is much evidence from studies of perception without attention that the initial filtering operations may involve such advanced functions as lexical and semantic processing (Luck et al., 1996; Maki, Frigen, et al., 1997; Visser, Merikle, & Di Lollo, 1998). Rather, the peripheral mechanisms must be regarded as integral parts of a more extensive filtering system comprising central as well as peripheral components. All parts of this system operate concurrently and interdependently and are dynamically reconfigured to meet the processing demands of the task at hand.

Concluding Remarks

Two related issues were examined in the present survey. One concerned Lag-1 sparing; we asked why it was obtained in some AB studies but not in others. The answer was unambiguous: the greater the similarity between T1 and T2, the greater is the probability of Lag-1 sparing. Specifically, Lag-1 sparing is found when two targets are similar and an attentional switch between them is not required or when such a switch involves a single dimension (i.e., a switch in task or category). Lag-1 sparing fails to appear with switches in location or with concurrent switches involving two or more dimensions. On the strength of these observations, we revised the attentional-gating hypothesis, which held that Lag-1 sparing occurs when T1 and T2 fall within the same temporal window of attention. In the revised hypothesis, two conditions must be met for Lag-1 sparing to occur: The two targets must be presented within a critical temporal interval, and both must match the characteristics of an input filter initially set for T1. The revised hypothesis leads to an explicit model in which the input filters are set under the control of signals originating from brain centers as high as prefrontal cortex. Such a model subsumes the conceptually driven filtering operations postulated by Shapiro and Raymond (1994) and Chun and Potter (1995) in their accounts of the AB deficit.

Strong evidence of independence between Lag-1 sparing and the AB deficit speaks to the other major issue examined in this survey, namely, how the cognitive system reconfigures itself in response to rapidly changing processing requirements. What emerges from the empirical evidence is a scheme of foci of control wherein early input filters come under a good deal of endogenous control, whereas domain-specific modules at later stages are triggered by exogenous signals that have passed through the input filters. The functional organization of the brain subserving this scheme resembles less a unitary central processor than an aggregate of domain-specific modules that operate in parallel on different attributes of the incoming stimuli.

Aside from being congruous with functional neuroanatomy, the present scheme of conceptually driven input filters and domain-specific high-level modules provides a remarkably consistent account of the behavioral evidence. An additional, if unanticipated, facet of this scheme is that it has the potential of reconciling conflicting views of the role of similarity in processing concurrent stimuli. Similarity is known to facilitate processing in some cases but to interfere with it in others. As shown in Table 2, the presence of Lag-1 sparing indicates that the greater the similarity between two stimuli, the greater the probability that they can be processed together. Conversely, it is well known that performance is substantially impaired when performing two similar tasks simultaneously, such as monitoring two concurrent verbal messages (Broadbent, 1958, 1984). Yet, dual-task interference all but vanishes if the two tasks are sufficiently different from each other. For example, Allport et al.'s (1972) participants could sight-read a piece of music while shadowing a spoken passage with much the same accuracy as when performing each task alone. In brief, similarity helps for Lag-1 sparing (Table 1) but hurts for dual-task performance.

These opposite effects can potentially be explained within the present scheme. For Lag-1 sparing, similarity between T1 and T2 is helpful because both targets can pass through the same input filter, thus gaining access to the same domain-specific module. For dual-task performance, on the other hand, similarity hurts because two streams of relatively complex stimuli compete for the same high-level module. This hypothesis is far from complete and is clearly in need of empirical evaluation. Nevertheless, we believe it worth pursuing because it offers a potential reconciliation between the opposite effects of similarity.

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