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The role of task-irrelevant information in perceptual learning

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ABSTRACT

(English)

In human perception, visual perceptual learning is a well-known effect, showing that the adult neural system can achieve long-term enhanced performance on a visual task as a result of visual experience (Fahle & Poggio, 2002). The mechanisms underlying visual perceptual learning were debated for decades. Task-relevance, attention and awareness were thought necessary for perceptual learning (Shiu & Pashler, 1992; Ahissar & Hochstein, 1993; Schoups, Vogel, Qian, and Orban, 2001), but this view has been challenged by the discovery of task-irrelevant perceptual learning (TIPL), which occurs for task-irrelevant, unattended and even sub-threshold stimuli (Watanabe, Nanez & Sasaki, 2001). TIPL is a slow phenomenon, because thousands of training trials are necessary in order to observe perceptual learning for task-irrelevant stimuli. However, a fast form of TIPL (fast-TIPL) has been recently studied in the context of perceptual memories, accounting evidence of a learning mechanism similar to TIPL, in which task-irrelevant stimuli are better learned when presented at behaviourally relevant points in time (Lin, Pye, Murray & Boynton, 2010).

In the present dissertation, the role of task-irrelevant stimuli in visual perceptual learning is examined. The first line of experiments aimed to deepen the understanding about the mechanisms underlying visual perceptual learning by investigating whether perceptual learning can be produced by the mere exposure to a task-irrelevant, sub-threshold feature, even when, during training, participants attend and perform a task on another feature of a homologous stimulus to that used during test stages. Additionally, the task-specificity of TIPL was examined. The results provided further evidence about TIPL by corroborating the hypothesis that TIPL can occur even when the training stimuli are homologous to those in pre- and post-test. A further interesting finding was that the visual perceptual learning yielded by the task-irrelevant and sub-threshold feature is task-specific, because it occurs only in the task for which participants received a specific training, and is not transferred to another task

performed on the same stimulus. Second, it has been investigated whether and how the modulation of the primary task difficulty level affects TIPL, by using a fast-TIPL paradigm which allows to study the phenomenon of TIPL within a single experimental session. In a dual-task condition, the amount of attention towards task-irrelevant stimuli which is needed for fast-TIPL to be observed was investigated by modulating the attentional and cognitive load of the primary task. The results showed a massive dual-task interference between the processing of primary task stimuli and the processing and encoding of task-irrelevant stimuli: the increase in the attentional and cognitive load required by the primary task determined a complete depletion of attentional resources such as no other resources remained available to process the task-irrelevant stimuli.

ABSTRACT

(Italiano)

Nel campo di ricerca della percezione visiva, il termine apprendimento percettivo identifica un miglioramento della performance in un compito visivo, ottenibile a lungo termine per effetto della semplice esposizione allo stimolo (Fahle & Poggio, 2002). I meccanismi alla base dell'apprendimento percettivo visivo sono tutt'oggi oggetto di dibattito. I primi studi in questo campo suggerivano l'esistenza di tre condizioni necessarie per il verificarsi dell'apprendimento: rilevanza dello stimolo per il compito, attenzione verso lo stimolo e consapevolezza dello stimolo (Shiu & Pashler, 1992; Ahissar & Hochstein, 1993; Schoups, Vogel, Qian, and Orban, 2001). Questa visione è cambiata in seguito alla dimostrazione dell'esistenza di un tipo di apprendimento percettivo, chiamato *task-irrelevant perceptual learning* (TIPL), in cui vengono appresi stimoli che sono irrilevanti per il compito, a cui non viene prestata attenzione e che vengono presentati sotto-soglia e quindi non possono essere percepiti coscientemente (Watanabe, Nanez & Sasaki, 2001). Il TIPL è tuttavia un meccanismo di apprendimento "lento": per osservare TIPL di uno stimolo sono infatti necessarie migliaia di prove. Recentemente è stato però scoperto un altro meccanismo di apprendimento, denominato fast-TIPL, molto simile (in quanto in entrambi i fenomeni uno stimolo non rilevante per il compito viene appreso se presentato in concomitanza di un evento rilevante), ma al contempo più "veloce" (Lin, Pype, Murray & Boynton, 2010).

Argomento generale della tesi è lo studio del ruolo delle informazioni irrilevanti per il compito nell'ambito dell'apprendimento percettivo visivo. I primi esperimenti sono stati condotti allo scopo di approfondire la comprensione dei meccanismi che sottendono l'apprendimento percettivo. È stato indagato e confermato sperimentalmente che l'apprendimento percettivo può essere prodotto dalla mera esposizione ad una caratteristica di uno stimolo anche quando quest'ultima non è rilevante per il compito, viene presentata sotto-soglia e quando durante la fase di addestramento i partecipanti svolgono il compito prestando attenzione a un'altra

caratteristica del medesimo stimolo usato durante le fasi di test. Inoltre, i risultati hanno mostrato specificità del TIPL rispetto al compito: l'apprendimento mostrato dai partecipanti alla fine della fase di addestramento non veniva trasferito ad altri compiti svolti sul medesimo stimolo. Successivamente è stato studiato se e come la modulazione della difficoltà del compito primario può influire sul TIPL, avvalendosi dell'uso di un paradigma fast-TIPL che permette di osservare il TIPL in una singola sessione sperimentale. Nello specifico, utilizzando un paradigma di doppio compito e modulando il carico attentivo e cognitivo elicitato dal compito primario, si è voluta indagare la quantità di attenzione diretta agli stimoli irrilevanti per il compito necessaria al verificarsi del TIPL. I risultati hanno mostrato una netta interferenza tra l'elaborazione degli stimoli del compito primario e l'elaborazione e la successiva codifica degli stimoli irrilevanti per il compito: tutte le risorse attentive sono state reclutate nel processo di elaborazione degli stimoli del compito primario rendendo impossibile l'elaborazione e la codifica degli stimoli irrilevanti per il compito.

DISSERTATION OVERVIEW

The chapters of the present dissertation have been organized in such a way as to introduce the reader to the two main studies that I conducted, firstly by providing a review of the literature needed to understand the theoretical framework of the experiments, and secondly by giving a detailed description of the experiments.

Chapter 1 contains a review of the literature regarding the phenomenon of TIPL, while Chapter 2 presents the study on TIPL carried out at the Ecole Polytechnique Fédérale de Lausanne (EPFL). In Chapter 3 the literature regarding the phenomenon of fast-TIPL is reviewed, while Chapter 4 describes the study about fast-TIPL.

At the end, a final conclusion is provided.

CHAPTER 1

Task-irrelevant perceptual learning

1.1 CHAPTER OVERVIEW

In this chapter, the phenomenon of task-irrelevant perceptual learning (TIPL) is described in detail. Starting from the early studies, which postulated that attention is necessary in visual perceptual learning, it is shown how the discovery of TIPL led to a reassessment of the role of attention. The constraints necessary for TIPL to occur are then discussed, because they shed light on how to reconcile the conflicting research findings emerging as regards the role of attention from studies on task-relevant perceptual learning (TRPL) and those on TIPL. A description is given of how attention can modulate TIPL, and a comparison is made between TRPL and TIPL studies to see whether the two learning mechanisms produce comparable learning effects. To clarify when TIPL occurs and what is changed through TIPL, the three main visual perceptual learning models (low-stage, mid-stage and late-stage) are described, and it is shown how the recently conceptualized dual plasticity model (DPM) can explain both TRPL and TIPL. Finally, the function of TIPL is examined in terms of ecological validity.

1.2 THE ROLE OF ATTENTION IN PERCEPTUAL LEARNING: EARLY FINDINGS

Although human perceptual systems are constantly bombarded with a huge amount of information from the environment which make it impossible to process and learn everything, they are nonetheless able to adapt rapidly and continually to the surrounding changing environment, also by becoming increasingly sensitive to behaviourally relevant information: this process is known as perceptual learning and it is considered a manifestation of neural plasticity (Fahle & Poggio, 2002).

In the domain of visual perception, it has been shown that after repeated practice (training),

the adult neural system can achieve long-term enhanced performance on a visual task: this phenomenon is known as visual perceptual learning (Fahle & Poggio, 2002). For a real-life example, an expert birdwatcher can easily discriminate between two birds from small differences in the pattern of colours of their plumage, while an untrained eye fails to see the differences. In a laboratory setting, a frequently used visual perceptual learning task is the Vernier task, in which a configuration of two or three stimuli is presented (usually lines or dots), and the subjects taking part in the experiment (henceforth described as participants) are asked to report whether the stimuli are aligned along a designated axis (for example, the vertical axis). After repeated practice, participants' performance usually improves (Fahle, Edelman, & Poggio, 1995).

One of the main issues in perceptual learning regards precisely what it is that gates this learning mechanism. In the last few decades, several studies have claimed that attention plays a fundamental role in gating perceptual learning (Shiu & Pashler, 1992; Ahissar & Hochstein, 1993; Schoups *et al.*, 2001). To better explain the role of attention in perceptual learning, a brief preamble is useful: in a perceptual learning task, an aspect of a stimulus (henceforth described as feature) or a stimulus that conveys information useful for performing a task is termed task-relevant, while those features or stimuli not directly used by participants to solve the task are termed task-irrelevant. A huge number of studies have found perceptual learning only for task-relevant features/stimuli, and not for task-irrelevant features/stimuli. The rationale behind this finding is that participants can show a sensitivity change only for features/stimuli to which they actively direct attention (task-relevant), whereas they do not show or show only a very limited performance improvement for features/stimuli to which they are merely exposed and not required to attend to (task-irrelevant). In other words, one of the prevailing hypotheses in the domain of perceptual learning was that, in order for a feature/stimulus to be learned, attention must be directed to it (Shiu & Pashler, 1992; Ahissar & Hochstein, 1993; Schoups *et al.*, 2001).

The following paragraphs takes a closer look at some of the studies which led to attention being considered as a gate mechanism for perceptual learning.

In 1992, Shiu and Pashler published a fundamental work, in which they examined, among other issues, the role of attention in a perceptual learning task (Experiment 3). Specifically, the authors studied whether participants' ability to discriminate a feature (task-irrelevant

feature) improves when participants attend and perform a task on another feature of the same stimulus (task-relevant feature). In other words, Shiu and Pashler (1992) were interested in demonstrating whether simply being exposed to a task-irrelevant feature is sufficient to observe perceptual learning of that feature. The experiment was divided into three successive stages: pre-test, training and post-test. During the pre- and post-test, participants performed an orientation discrimination task (i.e., they had to report whether a pair of straight lines had the same or different orientation). During the training, participants performed a brightness discrimination task based on the same stimulus used in the pre-test (i.e., they had to report whether the pair of straight lines had the same or different brightness¹). The results indicated that during the training participants showed visual perceptual learning for the task-relevant feature brightness (i.e., the performance in the brightness discrimination task was better at the end of the training compared to that measured at the beginning of the training), but visual perceptual learning was not found for the task-irrelevant feature orientation (i.e., the comparison between pre- and post-test in the orientation discrimination task revealed no significant differences in performance between the two stages²). In other words, attending to the brightness of the pair of straight lines does not influence the performance in the orientation discrimination task. In conclusion, the study by Shiu and Pashler (1992) showed that visual perceptual learning cannot be produced by the mere exposure to a task-irrelevant feature: attention to a feature is necessary for visual perceptual learning to occur (Shiu & Pashler, 1992).

The study by Ahissar and Hochstein (1993) came to exactly the same conclusion. It investigated whether practising a perceptual learning task leads to a performance improvement in another perceptual learning task, when the same visual stimuli are used in

¹ During training, the difficulty level of the brightness discrimination task was manipulated. One group of participants performed an “easy” brightness discrimination task (i.e., the difference in luminance between the two lines was 27 cd/m², with one line presented at a luminance of 21 cd/m² and the other at a luminance of 48 cd/m²). The other group of participants performed a “difficult” brightness discrimination task (i.e., the difference in luminance between the two lines was 17 cd/m², with one line presented at a luminance of 31 cd/m² and the other one at a luminance of 48 cd/m²). Participants who performed the “easy” brightness discrimination task showed higher accuracy (throughout the entire course of training) compared to participants who performed the “difficult” brightness discrimination task. However, there was no correlation between this difference in performance and the performance in the orientation discrimination task (Shiu & Pashler, 1992).

² The performance in the orientation discrimination task in the post-test was slightly better than in the pre-test, but this difference was due to a mere practice effect (Shiu & Pashler, 1992).

both tasks. In this study, participants were presented with an array of segments (tilted with respect to the vertical axis) and they had to perform two separate tasks: a global detection task and a local detection task. In the global detection task, participants had to judge whether the array of segments was vertical (i.e., designed with 5 rows and 6 columns of segments) or horizontal (i.e., designed with 6 rows and 5 columns of segments). In the local detection task, participants had to detect whether the array contained an odd element (i.e., the task was a classical pop-out task). The visual stimuli and consequently the retinal representation of the stimuli were the same in both tasks, and the difficulty level of the two tasks was comparable. The only difference between the global detection task and the local detection task was the task-relevant feature, which was respectively the global orientation (i.e., the orientation of the array) or the local orientation (i.e., the orientation of one segment). The results showed that practising the global detection task has no effect on performance in the local detection task, and vice versa (although the same visual stimuli were used in both tasks)³. To explain this finding, the authors suggested focusing on the difference between task-relevant and task-irrelevant features and the role of attention: for example, when the global detection task was performed, the task-relevant feature was the orientation of the array, and the task-irrelevant feature was the orientation of one segment. Again, as in the study by Shiu and Pashler (1992), perceptual learning occurs only for the task-relevant feature, and not for the simultaneously presented task-irrelevant feature. In conclusion, participants learned features to which their attention was voluntarily directed (because it was necessary to solve the task), while unattended features were not learned, demonstrating that attention is necessary to gate visual perceptual learning (Ahissar & Hochstein, 1993).

The two studies described above attribute a crucial role to attention (and therefore to top-down gating processes) in perceptual learning. Moreover, both sets of findings suggest that perceptual learning is associated with changes in the early visual cortex areas (where distinctive orientations are handled by separate channels), but that a high-level attentional

³ This result was obtained both when a variable association between stimuli and responses was used, and when constant association between stimuli and responses was preserved. Here is an example of the constant association between stimuli and responses: participants had to give the same response when they saw the “vertical” array (global detection task) and the presence of an odd element (local detection task), and another response when they saw the “horizontal” array (global detection task) and the odd element was not present (local detection task).

mechanism, controlling changes at low-level processing, is fundamental for perceptual learning to occur.

The role of attention in perceptual learning has also been explored in animal cognition and electrophysiological studies (Li *et al.*, 2004b; Op de Beeck, Wagemans, Vogels, 2007; Polley, Steinberg, & Merzanich, 2006). Polley and colleagues (2006) came to similar conclusions to the psychophysical studies described above (Shiu & Pashler, 1992; Ahissar & Hochstein, 1993), although they assessed perceptual learning in the auditory modality. The authors trained two groups of rats to attend either to the frequency (Group 1, performing a frequency recognition task) or to the intensity (Group 2, performing a loudness recognition task) of auditory stimuli (i.e., the authors trained two distinct dimensions of the same auditory stimuli, thereby keeping the sensory inputs constant). Both groups showed a significant improvement in performance after the training (i.e., perceptual learning), but this improvement was specific for the trained dimension only (task-relevant feature). In other words, despite being exposed to both stimuli dimensions (both frequency and intensity), perceptual learning was found only for the task-relevant feature (frequency in Group 1, and intensity in Group 2), and not for the task-irrelevant feature (intensity in Group 1, and frequency in Group 2). Once the training was completed, the authors recorded the electrophysiological responses, and found plasticity in the primary auditory cortex (AI) and in the suprarhinal auditory field (SRAF) for the task-relevant feature only⁴. On the basis of their finding that cortical map plasticity was limited to the feature that was relevant to solving the task, the authors concluded that cortical map plasticity is guided by top-down factors (for example, attention)⁵ (Polley *et al.*, 2006).

⁴ Rats trained in the frequency recognition task (Group 1) showed an expanded representation of the target frequency range within the tonotopic cortical map, while rats trained in the loudness recognition task (Group 2) showed an increased proportion of non-monotonic intensity response profiles preferentially tuned to the target intensity range (Polley *et al.*, 2006).

⁵ If cortical map plasticity was guided by “bottom-up” factors, they reasoned that cortical map plasticity should have been found in both stimuli dimensions, irrespective of whether these were task-relevant or task-irrelevant (Polley *et al.*, 2006)

1.3 TASK-IRRELEVANT PERCEPTUAL LEARNING

The expression *task-irrelevant perceptual learning* (TIPL) has been coined to denote a type of perceptual learning which occurs for stimuli that have no task-relevance, that are unattended and presented at a sub-threshold level (for a review, see Watanabe & Sasaki, 2015).

The phenomenon of TIPL was first described by Watanabe and colleagues (Watanabe *et al.*, 2001). This ground-breaking study made use of a specific experimental paradigm which has since been used extensively in a large number of TIPL studies. For this reason, it is important to describe the experimental paradigm in detail. The study consisted of three main experiments. The first experiment was divided into three consecutive stages: pre-test, training (or exposure) and post-test (Figure 1.1, panel a). During the pre-test, participants performed a motion direction identification task on a dynamic random dot (DRD) display⁶. In each trial of the motion direction identification task, one out of eight motion directions at 5% or 10% of coherent motion level was presented, and participants were required to report the perceived motion direction (Figure 1.1, panel c). Then, during the training, participants performed a primary task in the fovea consisting of a rapid serial visual presentation (RSVP) identification task: participants were required, at the end of each trial, to report the identity of the two RSVP targets (two grey letters), which were presented among RSVP distractors (black letters). While performing the primary task, participants were also exposed in the peripheral visual field to a designated motion direction presented at 5% of coherent motion level on the DRD display (Figure 1.1, panel c). The use of 5% coherent motion level on the DRD display during the training was justified by the fact that in a preliminary experiment this value was demonstrated to be sub-threshold⁷. The training was extensive, because it lasted for 20 days. Once participants completed the training, they underwent the post-test, in which they were evaluated on the same task and using the same procedure adopted in the pre-test.

⁶ A dynamic random dot (DRD) display is a visual stimulus consisted of a large number of moving dots; typically, a small number of moving dots moves coherently representing motion signal, which is embedded within a background of randomly moving dots representing noise.

⁷ In a preliminary experiment on six participants, the authors found that the coherence motion detection threshold was 8.3% of coherent motion level (Watanabe *et al.*, 2001).

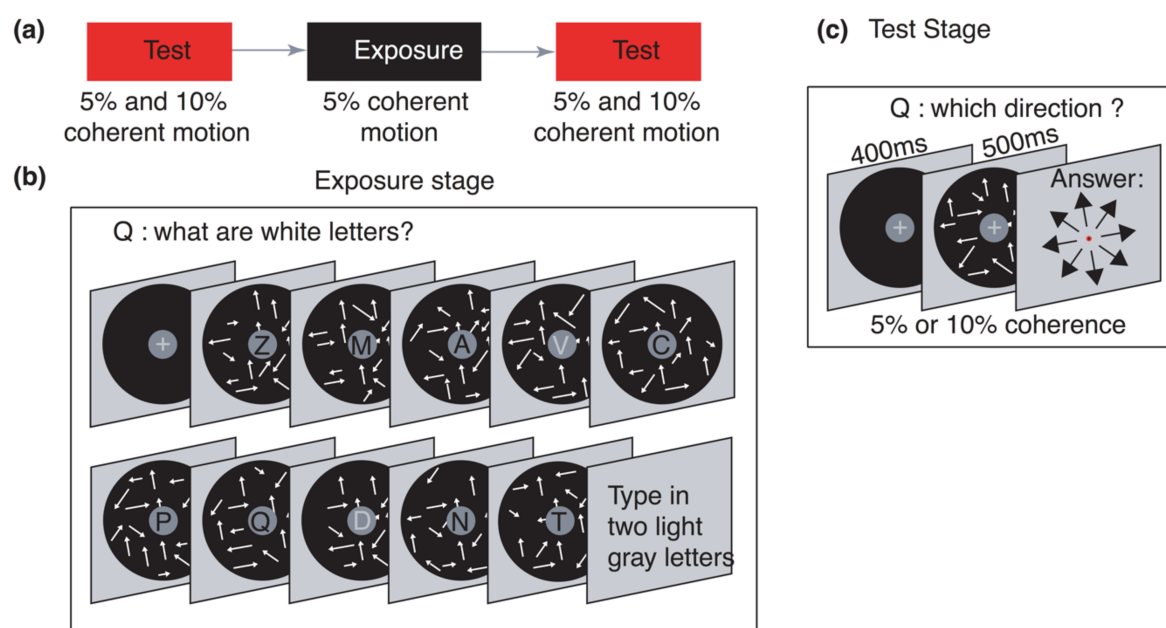


Figure 1.1 - Schematic of the experimental procedure and tasks used in Watanabe and colleagues (2001). Panel (a): experimental procedure; panel (b): example of a training trial: participants performed a central RSVP identification task, while they were exposed to task-irrelevant and sub-threshold motion direction; panel (c): example of a test trial: participants performed a direction identification task (image taken from reference: Seitz & Watanabe, 2005).

The results showed a significant pre-/post-test performance improvement in the direction identification task only for the motion direction to which participants were exposed during the training, indicating the occurrence of visual perceptual learning for a stimulus which was task-irrelevant (the coherently moving dots were irrelevant to solving the primary task), unattended (the coherently moving dots were presented in the peripheral visual field, while participants' attention was directed at the centre of the screen where the RSVP identification task was presented), and sub-threshold (see footnote 7). In other words, in this initial experiment, Watanabe and colleagues (2001) showed for the first time that visual perceptual learning can be produced by the mere exposure to stimuli on which participants do not have to perform a task, to which they are not required to pay attention, and of which they have no awareness (because the motion direction was presented sub-threshold) (Watanabe *et al.*, 2001). Moreover, the authors replicated the same finding in other two experiments, using different tasks in the pre- and post-test (i.e., binary motion detection task and 2 AFC motion detection task) (Watanabe *et al.*, 2001).

In 2003, Seitz and Watanabe published another fundamental TIPL study which showed that this learning mechanism is not purely passive, as hypothesized in the previous work (Watanabe *et al.*, 2001). TIPL occurs as result of exposure to task-irrelevant, unattended, and sub-threshold stimuli; however, a repetitive mere exposure to those stimuli is not sufficient to observe TIPL because this learning mechanism results from reinforcement by the primary task. To demonstrate this, the authors modified the experimental paradigm used in Watanabe and colleagues (2001), this time introducing four different motion directions of the DRD display during the training: one motion direction (for example, upward) was always paired with the occurrence of the RSVP targets (white letters), while the other three motion directions were randomly paired with the RSVP distractors (black letters). Moreover, the four different motion directions were presented at a sub-threshold level (i.e., each motion direction was presented at 5% of coherent motion level), and an equal number of times during the training (Figure 1.2).

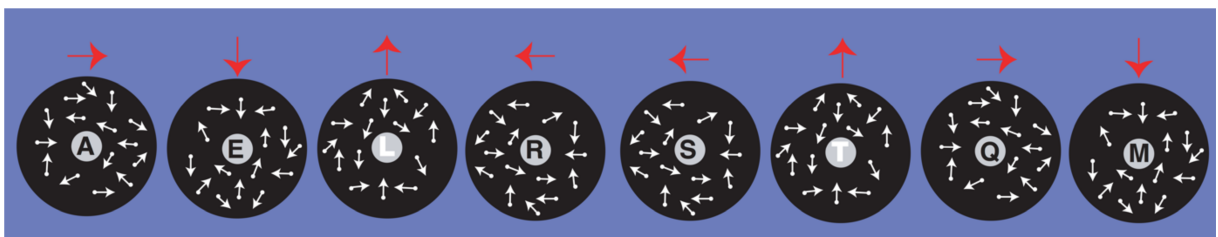


Figure 1.2 - Schematic of the training procedure used in Seitz and Watanabe (2003). One designated motion direction was always paired with the occurrence of the RSVP targets (white letters), while other motion directions were randomly paired with the occurrence of the RSVP distractors (black letters) (image taken from reference: Seitz & Watanabe, 2005).

If the mere exposure to task-irrelevant, unattended and sub-threshold stimuli was sufficient for TIPL to occur, a pre-/post-test performance improvement for all four different motion directions (to which participants were exposed) would be expected. Instead, the results showed a significant pre-/post-test performance improvement only for the motion direction paired with the RSVP targets, and not for the other three paired with the RSVP distractors. Two alternative explanations might account for these results. The first explanation is that the

simultaneous occurrence of the RSVP target and of the task-irrelevant stimulus produces TIPL (i.e., TIPL as a mechanism that promotes perceptual learning); the second explanation is that the simultaneous presentation of the RSVP distractors and of the task-irrelevant stimuli prevents TIPL from occurring (i.e., TIPL as a mechanism that inhibits perceptual learning). In order to test these two possible explanations, the authors carried out a control experiment which showed that TIPL originates from reinforcement by the primary task; specifically, the internal reinforcement produced by the detection of the RSVP targets is responsible for TIPL (Seitz & Watanabe, 2003).

In conclusion, it has been demonstrated that the perceptual learning of a task-irrelevant, unattended, and sub-threshold stimulus is positively correlated with the occurrence of a task-relevant stimulus.

1.4 THE CONSTRAINTS OF TASK-IRRELEVANT PERCEPTUAL LEARNING

After the publication of the two most influential studies about task-irrelevant perceptual learning (TIPL) (Watanabe *et al.*, 2001; Seitz & Watanabe, 2003; for a detailed description of the studies, see the previous paragraph), numerous experiments have been conducted in an attempt to improve the understanding of this learning mechanism, with particular attention paid to the conditions necessary for TIPL to occur.

1.4.1 Target (high-level processing) – task-irrelevant stimulus temporal association

One of the constraints for TIPL to occur is the temporal association between the high-level processing of the task-relevant stimulus of the primary task (i.e., the target) and the occurrence of the task-irrelevant stimulus.

In 2003, Seitz and Watanabe demonstrated that the temporal association between the occurrence of an RSVP target and a task-irrelevant stimulus is necessary for TIPL, because the detection of a target triggers an internal process of reinforcement which in turn promotes learning of task-irrelevant stimuli temporally paired with the target occurrence. Thus, TIPL is not a passive phenomenon (Seitz & Watanabe, 2003).

However, the critical factor for TIPL to occur is not the temporal association between the target and the task-irrelevant stimulus *per se*. In order to obtain TIPL, the target has to be fully processed by the brain, i.e., correctly detected and identified. In other words, a high-level processing of the target is required because it is not the simple detection of the target, but it is the correct identification, that promotes a diffuse learning signal (i.e., a mechanism of internal reinforcement), which in turn determines the learning of the task-irrelevant stimuli temporally paired with the target (Seitz, Nanez, Holloway, Koyama, & Watanabe, 2005).

Seitz and colleagues (2005b) used the attentional blink (AB)⁸ experimental paradigm in order to investigate the level of target processing necessary for TIPL. If TIPL occurs during the temporal window of AB, it means that a low-level processing of the target (for example a perceptual processing) is required for TIPL, whereas if TIPL does not occur during the AB, it means that TIPL requires a high-level processing of the target (for example a successful identification). The experiment was divided into three consecutive stages: pre-test, training and post-test. During the pre- and post-test, participants performed a direction identification task on a dynamic random dot (DRD) display. During the training, which lasted ten days, participants performed a rapid serial visual presentation (RSVP) task (primary task). The RSVP task was presented in the fovea and participants were instructed to respond to two targets (T1 and T2, two digits) presented among distractors (letters). While performing the primary task, participants were exposed in the peripherally visual field to several motion directions presented at 5% of coherent motion level on the DRD display. Two different motion directions were paired with the occurrence of the second target (T2): one motion direction was presented within the AB temporal window (AB condition; T1-T2 SOA:200 ms), while the other was presented outside the AB temporal window (NoAB condition; T1-T2 SOA:800 ms). The

⁸ The attentional blink (AB) is a phenomenon described for the first time by Raymond, Shapiro and Arnell (1992), which refers to the impossibility to identify or to recognize a target (T2) when it is presented soon after another target (T1). The AB can shed light on the limits of the cognitive system: one or more elaboration stages of T1 interfere with the elaboration of T2, making it impossible (Chun & Potter, 1995; Jolicoeur, 1999). The AB experimental paradigm typically involves using a RSVP task, in which two targets have to be identified while being presented sequentially between other stimuli (distractors). When the temporal window between the presentation of the first and the second target (stimulus onset asynchrony, SOA) is less than 500-600 ms, it is possible to observe the AB (Shapiro, 2001). It should be pointed out that it is impaired high-level processing of the target (for example failure to identify or recognise the target) that produces the AB, and that the AB is not produced by a problem in low-level processing (for example at the perceptual or semantic level) (Luck, Vogel, & Shapiro, 1996; Shapiro, Arnell, & Raymond, 1997).

results showed a significant pre-/post-test performance improvement in the direction identification task only for the motion direction presented in the NoAB condition. This proves that when participants fail to identify the target (i.e., AB condition), the learning of the task-irrelevant stimuli simultaneously paired with the target does not occur, corroborating the idea that a high-level processing of the target is required for TIPL to occur (Seitz *et al.*, 2005b).

1.4.2 Reward – task-irrelevant stimulus temporal association

Another constraint for TIPL to occur is the temporal association between the occurrence of a rewarding stimulus (henceforth described as reward⁹) and the task-irrelevant stimulus.

There are two distinct types of reward: internal and external. The term *internal reward* refers to a self-generated (endogenous) reward, while the term *external reward* refers to an external (exogenous) reward.

An example of TIPL generated by the temporal association between the occurrence of an internal reward and a task-irrelevant stimulus, was first described by Seitz and Watanabe in 2003 (for a detailed description of the study, see paragraph 1.3). The authors demonstrated that the successful detection of a target promotes an internal reward mechanism, which in turn gives rise to the learning of the task-irrelevant, unattended, and sub-threshold stimulus temporally paired with the occurrence of the internal reward (Seitz & Watanabe, 2003). More specifically, it has been hypothesized that successful performance in a primary task stimulates the release of various neuromodulators such as acetylcholine, norepinephrine, and dopamine, which are known to be released diffusely throughout in the brain as a response to certain behaviourally relevant events (Schultz, Dayan, & Montague, 1997; Pearce & Bouton, 2001; Dayan & Balleine, 2002; O'Doherty *et al.*, 2006), and which play an important role in the learning process (for reviews, see Seitz & Watanabe, 2005; Seitz & Dinse, 2007).

In 2009, it was shown that TIPL can also occur as the result of a temporal association between an external reward and the occurrence of a task-irrelevant, unattended, and sub-threshold stimulus, in the absence of an explicit task (therefore without a temporal association between

⁹ "any stimulus, object, event, activity, or situation that has the potential to make us approach and consume it is by definition a reward" (Schultz, 2015, page 855).

a target and a task-irrelevant stimulus) and without participants' consciousness of the reward contingences (Seitz, Kim & Watanabe, 2009). It is well known that learning signals are triggered by task-context (i.e., learning signals are triggered by a successful performance in a given task) (Schultz, 2000; Dalley *et al.*, 2001), but they are also released outside the task-context in the presence of rewards and in the context of classical conditioning (Schultz *et al.*, 1997; Pearce & Bouton, 2001; Thiel, Friston, & Dolan, 2002; Yu & Dayan, 2005; O'Doherty *et al.*, 2006). The study by Seitz and colleagues (2009) is based on this assumption. The authors did two experiments, and in both they used a classical conditioning experimental paradigm: participants were exposed to task-irrelevant stimuli, and received an external reward without any precise temporization. To be more precise, the first experiment consisted of three stages: pre-test, training and post-test. During the pre- and post-test, participants performed an orientation discrimination task on Gabor patches¹⁰. During the training, which lasted 9 days, participants were exposed to Gabor patches, which were presented at a sub-threshold contrast with respect to the background; a designated angle-of-orientation of the Gabor patches (trained orientation) was systematically temporally paired (i.e., preceded and partially overlapped) with the occurrence of an external reward (i.e., a drop of water)¹¹, while another angle-of-orientation was presented without the temporal association with the external reward (control orientation). It is important to underline that during the training, participants were not required to perform a task, but instead passively viewed the computer monitor¹² on which the Gabor patches were presented (Figure 1.3).

¹⁰ Gabor patches are sinusoidal gratings with a Gaussian envelope.

¹¹ In order to make the drop of water an effective rewarding stimulus, participants were deprived of food and water for 5 hours before the experiment began. The choice of rewarding participants with water was motivated by the fact that a liquid reward produces a well-characterized physiological response that has been shown to have effects on human brain processing (O'Doherty, Deichmann, Critchley, & Dolan, 2002; Gottfried, O'Doherty, & Dolan, 2003; Mitz, 2005; O'Doherty, Buchanan, Seymour, & Dolan, 2006), and because it makes it possible to compare the learning results with those obtained in animal studies which used food or liquids as rewards.

¹² During the training, participants were only required to keep their gaze on a fixation point placed at the centre of the computer monitor, and were told to enjoy the occasional drops of water that were delivered to them.

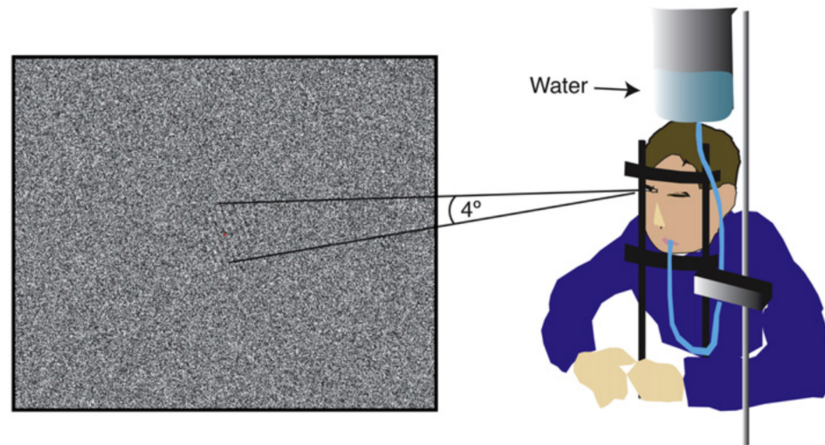


Figure 1.3 - Schematic of the experimental setting used during training in Seitz and colleagues (2009). Participants were instructed to passively view a computer monitor (the stimuli to which participants were exposed were sub-threshold, thus imperceptible to them), and to enjoy the drops of water randomly delivered to them (image taken from reference: Seitz *et al.*, 2009).

The results showed a significant pre-/post-test performance improvement in the orientation discrimination task only for the trained orientation, which during training was paired with the occurrence of the external reward, and not for the control orientation. In other words, TIPL can occur automatically as a result of external reward – task-irrelevant stimulus temporal pairing. In the second experiment, an analogous procedure was implemented (i.e., participants performed sequentially a pre-test, a training, and a post-test), but this time the experimental paradigm of continuous flash suppression (CFS)¹³ was used, in order to make the Gabor patches truly imperceptible (Tsuchiya & Koch, 2005) and to prevent participants from deducing the stimulus-reward contingencies. The pattern of results was similar to that obtained in the first experiment. Moreover, no transfer of learning was observed between the two eyes (i.e., TIPL was found only for the eye to which Gabor patches were presented); the finding of ocular specificity might indicate that the formation of TIPL occurs at early stages of

¹³ In the continuous flash suppression (CFS) experimental paradigm, one eye is presented with a static stimulus (in this experiment with two angle-of-orientation of Gabor patches), while the other eye is presented with continuously flashing stimuli (in this experiment with contour rich patterns). As a result of this procedure, the static stimulus becomes no longer detectable because of the continuously flashing stimuli presented to the other eye (i.e., the static stimulus is consciously repressed by the continuously flashing stimuli). At the neuronal level, the activity of the majority of binocular neurons is dominated by the continuously flashing stimuli rather than by the static stimulus (Tsuchiya & Koch, 2005).

visual processing¹⁴ (Seitz *et al.*, 2009).

The work previously described (Seitz *et al.*, 2009) represents a challenge to the large number of perceptual learning theories which postulate that for perceptual learning to occur, task-related reinforcement signals are necessary (Herzog & Fahle, 1997; Roelfsema & van Ooyen, 2005; Seitz, Lefebvre, Watanabe, & Jolicoeur, 2005; Seitz & Watanabe, 2005; Petrov, Doshier, & Lu, 2006). Although the study by Seitz and colleagues (2009) was the first to show that the simple association between an external reward and a task-irrelevant stimulus is enough to trigger perceptual learning in a behavioural experimental paradigm, other studies had previously demonstrated that it is possible to induce perceptual learning, and thus plasticity of the sensory systems, by passive stimulation (for example, Frenkel *et al.*, 2006; Dinse *et al.*, 2006; for a review, see Seitz & Dinse, 2007), or by the use of electrical and magnetic stimulation (for example, Godde, Leonhardt, Cords, & Dinse, 2002; Tegenthoff *et al.*, 2005; for a review, see Seitz & Dinse, 2007). An example of plasticity induced by passive stimulation can be found in the work by Frenkel and colleagues (2006). The authors repeatedly exposed awake adult mice to a single orientation (horizontal) of a high-contrast grating stimulus, and they recorded visually evoked potentials (VEP)¹⁵ from primary visual cortex, in order to monitor whether and how cortical responses changed in time in response to the same visual stimulus. The results showed a persistent potentiation of the evoked responses related to the stimulus to which the mice had been passively exposed. To be more precise, the authors observed that the potentiation of the evoked responses was specific to the stimulus orientation. Moreover, a positive correlation was found between the number of the exposure sessions and the increase in the evoked responses. In conclusion, there is evidence that passive stimulation

¹⁴ The ocular-specific TIPL obtained in this study was considered proof that TIPL occurs at the early stages of visual processing (as demonstrated in physiological studies conducted in awake behaving macaques, in which it has been shown that learning takes place in V4 or earlier; Franko, Seitz, & Vogels, 2010). This conclusion was based on previous findings that considered ocular-specific learning to be a manifestation of plasticity of the early (and monocular) stages of visual processing (Karni & Sagi, 1991; Fahle *et al.*, 1995; Schoups *et al.*, 2001; Lu, Chu, Doshier, & Lee, 2005). However, it must be borne in mind that, although the incidence is low, it is possible to find ocular specificity also in the high-level visual areas (Uka, Tanaka, Yoshiyama, Kato, & Fujita, 2000), indicating that learning can also occur at late stages of visual processing (Ahissar & Hochstein, 2004). Moreover, there are opposite findings regarding ocular-specific learning: Karni and Sagi (1991), and Schoups and colleagues (2001), respectively found ocular-specific learning and ocular-transfer learning.

¹⁵ Visually evoked potentials (VEP) are electrical potentials triggered by visual stimuli (Sokol, 1976).

selectively enhances plasticity in the primary visual cortex¹⁶ (Frenkel *et al.*, 2006). As aforementioned, plasticity can also be induced by electrical stimulation. An example can be found in the work by Godde and colleagues (2002). After applying intracortical microstimulation (ICMS)¹⁷ in the visual cortical area 18 (i.e., the extrastriate occipital area) of adult cats for a few hours, they found that this stimulation led to a reorganization of the cortical representation at the ICMS site, and to changes in the layout of visual orientation preference maps (Godde *et al.*, 2002). A reorganization of the visual cortex can be also provoked by magnetic stimulation, using transcranial magnetic stimulation (TMS)¹⁸: plasticity can therefore be induced from outside the skull as well. Tegenthoff and colleagues (2005) showed that, in humans, a brief period (20 minutes) of 5 Hz TMS applied over the right index finger cortical representation of primary somatosensory cortex (S1), can induce a 2-hour perceptual¹⁹ and cortical²⁰ change (Tegenthoff *et al.*, 2005).

To conclude, one crucial point needs to be clarified. It has been argued (Seitz & Watanabe, 2003; Seitz *et al.*, 2009) that TIPL produced by the temporal association between an internal or external reward and the occurrence of a task-irrelevant stimulus resembles—classical conditioning, in which the pairing between a reinforcer and a stimulus gates learning without the requirement of awareness (Morris, Ohman, & Dolan, 1998; Schultz, 2000; Pessiglione *et al.*, 2008). However, there is an important difference between TIPL and classical conditioning: in TIPL the learning measure is the change in sensitivity to the task-irrelevant stimulus, while

¹⁶ Despite this evidence, there are several studies that did not find plasticity in V1 or V2 even after a prolonged passive stimulation (for example, Ghose, Yang, & Maunsell, 2002).

¹⁷ Intracortical microstimulation (ICMS) is an electrical stimulation technique, which consists of electrical currents (typically short and low-strength, but high-frequency) applied repeatedly using a microelectrode, in order to induce neuronal re-organizational processes (Binder, Hirokawa, & Windhorst, 2009).

¹⁸ Transcranial magnetic stimulation (TMS) is an electromagnetic stimulation technique based on Faraday's principles of electromagnetic induction, in which a magnetic field (generated by a current flowing through a coil of wire positioned above a human or animal head) passes through the scalp and the skull of the head, and it induces a secondary current in the brain, stimulating neural tissue (Pascual-Leone, Walsh, & Rothwell, 2000).

¹⁹ The perceptual change was assessed through a psychophysical experiment, and consisted of a significant pre-/post-TMS performance improvement (i.e., lower threshold of discrimination after TMS) in the two-point discrimination task in the stimulated finger (right index) (Tegenthoff *et al.*, 2005).

²⁰ The cortical change consisted of an expansion of the stimulated finger (right index) cortical representation assessed through BOLD signals change using functional magnetic resonance imaging (fMRI) (Tegenthoff *et al.*, 2005).

in classical conditioning the learning measure is the strength of the stimulus-response association. In this framework, the work by Seitz and colleagues (2009) has brought a better understanding of the mechanisms that promote TIPL, and of how to distinguish TIPL from other forms of learning (for example, classical conditioning) by reducing confounding factors such as the learning of decision strategies and/or the learning of stimulus-response mapping.

1.4.3 Para- or sub-threshold task-irrelevant stimulus

A necessary constraint for TIPL to occur is that the task-irrelevant stimulus should be presented at a para- or sub-threshold level.

Tsushima, Seitz and Watanabe (2008) demonstrated that TIPL occurs only for task-irrelevant stimuli presented at para- or sub-threshold levels, and not when participants are exposed to supra-threshold task-irrelevant stimuli or when the task-irrelevant stimuli are far below the threshold). In order to determine the relationship between the strength of the task-irrelevant stimulus and the magnitude of TIPL, the authors used an experimental paradigm which resembles that of Watanabe and colleagues (2001). The experiment was divided into three stages: pre-test, training and post-test. During pre- and post-test participants were required to perform a direction identification task on a dynamic random dot (DRD) display. During training, which lasted 10 days, participants performed a primary task in the fovea consisting of a rapid serial visual presentation (RSVP) task (the targets were two digits presented amongst distractor letters), while being exposed in the peripherally visual field to several motion directions on the DRD display. The novelty of this study is that the authors paired two motion directions, each one presented at a different coherent motion level, with the RSVP targets. Specifically, one motion direction was presented at a low level of motion coherence (3% or 5% coherent motion level), while the other was presented at a higher level of motion coherence (15% or 50% coherent motion level)²¹. Other motion directions were randomly paired with the occurrence of the RSVP distractors. Contrary to the intuitive hypothesis that the coherent motion level would be positively correlated with the TIPL magnitude, the results (comparing pre-/post-test performance improvement in the direction identification task)

²¹ Participants were divided into four groups; each group was respectively exposed to: 3% and 15%, 3% and 50%, 5% and 15%, or 5% and 50% coherent motion levels.

showed that TIPL occurred only for task-irrelevant stimuli presented at 5% (sub-threshold) and 15% (para-threshold) coherent motion levels, and not when participants were exposed to 3% (indicating that the task-irrelevant stimulus was too weak) or to 50% (supra-threshold) coherent motion levels. To explain these results, the authors argued that task-irrelevant stimuli presented at sub- or para-threshold levels fail to be detected by the attentional system and are therefore learned, while task-irrelevant stimuli presented at a supra-threshold level are detected and suppressed by the attentional system (attention-based suppression hypothesis) (Tsushima *et al.*, 2008; Roelfsema, van Ooyen, & Watanabe, 2010). In particular, it has been claimed that human lateral prefrontal cortex (LPFC)²² plays an important role in TIPL for motion stimuli (Tsushima *et al.*, 2008). It is known that the LPFC is responsible for the inhibitory attentional control on task-irrelevant coherent motion stimuli (Knight, Staines, Swick, & Chao, 1999), and that it has a higher response threshold for motion-direction stimuli than the middle temporal (MT) visual area²³, which is dedicated to the processing of motion direction (Tsushima, Sasaki, & Watanabe, 2006). Within this context, it is possible to assume that a task-irrelevant stimulus presented at a sub- or para-threshold level is not sufficient to cause the activation of LPFC, and thus that the learning of that task-irrelevant stimulus is not inhibited by the LPFC. However, the same task-irrelevant stimulus is sufficient to cause the activation of the MT visual area, which has a lower threshold of activation and which allows the learning of motion direction (Tsushima *et al.*, 2006). Thus, the task-irrelevant stimulus presented at 3% coherent motion level is too weak to activate the MT visual area (Britten, Shadlen, Newsome, & Movshon, 1992; Rees, Friston, & Koch, 2000), and to give rise to the learning of motion direction, while the supra-threshold task-irrelevant stimulus (50% coherent motion level) is strong enough to activate the LPFC, thereby triggering the inhibitory attentional control preventing TIPL (Tsushima *et al.*, 2008).

²² For a review of the structural and functional organization of the human lateral prefrontal cortex, see Petrides (2005).

²³ For a review of the structural and functional organization of the human middle temporal visual area, see Born and Bradley (2005).

1.4.4 Target – task-irrelevant stimulus spatial proximity

The last constraint postulates that spatial proximity is necessary between a primary task target and a task-irrelevant stimulus in order to observe TIPL.

In 2007, Nishina and colleagues explored how an increase in the spatial distance between a primary task stimulus (target) and a task-irrelevant stimulus could impact TIPL. Their experiment was divided into three main stages: pre-test, training and post-test. During pre- and post-test, participants performed an orientation discrimination task on Gabor patches presented in two different spatial locations of the visual field. During training, participants were required to perform a rapid serial visual presentation (RSVP) task (primary task) in a designated spatial location, while being exposed to different angle-of-orientation of the Gabor patches. The Gabor patches²⁴ were presented in two different spatial locations, with one location (close) being closer to the spatial location of the primary task than the other location (far). The association between the angle-of-orientation of the Gabor patch and its spatial location was fixed. The results showed a higher pre-/post-test performance improvement in the orientation discrimination task in the close than in the far condition, which indicates that the magnitude of TIPL is negatively correlated with the increase in spatial distance between primary task targets and task-irrelevant stimuli (i.e., spatial fall-off of learning). Thus, spatial proximity between primary task targets and task-irrelevant stimuli is indeed a constraint for TIPL to occur, although the brain mechanism responsible for this effect is still not understood (Nishina *et al.*, 2007).

1.5 ATTENTION IN PERCEPTUAL LEARNING: RECONCILING CONFLICTING FINDINGS

Is attention necessary in perceptual learning? A perusal of the preceding paragraphs will show that this is clearly not an easy question to answer, because the literature on this topic has produced conflicting findings: for this reason, the role of the attentional system in perceptual learning is still very much open to debate.

²⁴ The Gabor patches were presented at a sub-threshold contrast with respect to the background.

Some studies have claimed that attention is mandatory for perceptual learning to occur, because a feature or a stimulus can be learned only when participants direct their attention to it, while features or stimuli to which participants are only exposed and which are not attended to, are not learned (Shiu & Pashler, 1992; Ahissar & Hochstein, 1993).

In 2001, this view was challenged by the discovery of task-irrelevant perceptual learning (TIPL), in which perceptual learning can occur for stimuli to which participants do not direct their attention (and which are completely irrelevant to the task, and presented at a sub-threshold level) (Watanabe *et al.*, 2001).

At first glance, it might seem impossible to reconcile these conflicting findings. However, if we look more closely, there is an important difference between the first line of studies (Shiu & Pashler, 1992; Ahissar & Hochstein, 1993) and the second (Watanabe *et al.*, 2001) with regard to the properties of the task-irrelevant features or stimuli. In the studies by Shiu and Pashler (1992), and Ahissar and Hochstein (1993), participants were exposed to task-irrelevant features presented at a supra-threshold level, while in the study by Watanabe and colleagues (2001), the task-irrelevant stimuli were presented at a sub-threshold level. This crucial difference might account for the conflicting results found in the literature about the role of the attentional system in perceptual learning. It has been demonstrated that when a task-irrelevant stimulus is presented at a supra-threshold level, an attentional inhibition of that stimulus occurs, preventing TIPL. In other words, the attention-based suppression hypothesis formulated by Tsushima and colleagues (2008) postulate that task-irrelevant features or stimuli presented at a supra-threshold level are detected and consequently suppressed by the attentional system and thus not learned, while task-irrelevant stimuli presented at a sub- or para-threshold level are not detected by the attentional system (consequently not suppressed), thus enabling TIPL to occur (Polley *et al.*, 2006; Tsushima *et al.*, 2006; Tsushima *et al.*, 2008; Roelfsema *et al.*, 2010). Another finding (Paffen, Verstraten, & Vidnyanszky, 2008) confirmed the attention-based suppression hypothesis (Tsushima *et al.*, 2008), showing that when participants are trained on a task-relevant feature, this causes a decrease in sensitivity to the paired task-irrelevant feature (due to the attention-based suppression). This study explored how exposure to task-relevant and task-irrelevant features can affect the perceptual dominance of these features in binocular rivalry. Participants were first (pre-test) presented with a motion identification task on a dynamic random dot (DRD) display, in order to measure

the motion coherence thresholds for three motion directions (i.e., rightward, downward and control direction), and with a binocular rivalry task to assess the perceptual dominance of all three of the motion directions used in the previous task. Then (training), participants performed a two-interval forced-choice speed discrimination task on the DRD display: in this task, participants had to report which one of the two intervals contained the faster rightward motion (the other interval contained a downward motion presented at constant speed). This procedure makes it possible to distinguish between the task-relevant feature (rightward motion), and the task-irrelevant feature (downward motion). Subsequently (post-test), participants performed the same tasks as in the pre-test. The results showed a pre-/post-test performance improvement in the motion coherence thresholds for the task-relevant feature, and a pre-/post-test stronger suppression of the task-irrelevant feature during binocular rivalry. Overall, the results indicated that, subsequent to training, there is an increased inhibition of the task-irrelevant feature, demonstrated by the pre-/post-test decrease in the duration of the task-irrelevant feature perceptual (ocular) dominance (Paffen *et al.*, 2008).

Moreover, this same study (Paffen *et al.*, 2008) made an interesting suggestion on how to reconcile the conflicting results regarding the role of attention in perceptual learning. They proposed that it may not just be the difference in the supra-/sub-threshold properties of the task-irrelevant stimuli that accounts for the conflicting results: the relationship between the task-relevant and task-irrelevant features or stimuli also has to be considered. The authors cited the work by Polley and colleagues (2006), which stated that “*plasticity is restricted to the task-relevant domain only if stimuli in the task-irrelevant domain interfere with the ability to solve the task*” (Polley *et al.*, 2006, page 4981). In line with this hypothesis, Paffen and colleagues (2008) argued that the difference between early studies (Shiu & Pashler, 1992; Ahissar & Hochstein, 1993) and the more recent findings about TIPL (Watanabe *et al.*, 2001) is also due to the different type of feature/stimulus employed. In early studies, participants were required to perform a task on one specific feature of one stimulus; in other words, only one stimulus (presented in one spatial location) was employed and one selected feature relevant to solving the task was considered the task-relevant feature, while another feature irrelevant to solving the task was considered the task-irrelevant feature. In studies which demonstrated the TIPL effect, on the other hand, two different types of stimuli presented in two different spatial locations were employed. It is possible that in the early studies, the task-

irrelevant feature interfered with the execution of the training task and was thus actively inhibited by the attentional system, while in the TIPL studies, the exposure to a task-irrelevant stimulus unrelated to the ability to perform the training task might have prevented inhibition of that stimulus (Paffen *et al.*, 2008).

In conclusion, both lines of research about the role of the attentional system in perceptual learning are valid: it seems possible to observe TIPL when the task-irrelevant stimulus has sub-threshold properties or does not interfere with the execution of the training task, and not observe it when the task-irrelevant stimulus has supra-threshold properties or interferes with the training task.

1.6 HOW ATTENTION MODULATES TASK-IRRELEVANT PERCEPTUAL LEARNING

It should be pointed out that learning processes guided by attention (attentional learning processes) and task-irrelevant perceptual learning (TIPL) are not mutually exclusive phenomena, but operate together to gate learning. In this context, it is possible to hypothesize that the role of TIPL is to boost the processing of task-irrelevant, unattended and sub-threshold stimuli, while the role of attention is to choose which stimuli are important (and should thus as a consequence be processed and learned), and to suppress irrelevant information (Seitz & Watanabe, 2009).

In this framework, attention can modulate TIPL, as shown in the study by Tsushima and colleagues (2008), which found a correlation between the strength of the task-irrelevant stimulus and the magnitude of TIPL effect, indicating that when the task-irrelevant stimulus reaches the threshold of visibility and can thus be attended to, the attentional system inhibits that stimulus, preventing TIPL (Tsushima *et al.*, 2008). Another example of how attention can impact on TIPL can be found in the study by Choi, Seitz, and Watanabe (2009). In their experiment, the authors modulated attention by eliciting attentional orienting toward a designated location using an exogenous attention experimental paradigm. More specifically, the experiment was divided into three stages: pre-test, training and post-test. During pre- and post-test, participants performed a motion direction identification task on a dynamic random dot (DRD) display. During training, participants performed an orientation identification task

(primary task), in which they were asked to report the direction (left or right) of an arrow presented at the centre of the screen; at the same time, they were exposed to two DRD displays with 5% of dots moving in a coherent direction (the motion coherence was thus presented at a sub-threshold level) presented both left and right of the screen centre²⁵ (i.e., participants were exposed to two simultaneous task-irrelevant stimuli). The arrows of the primary task automatically directed attention towards one of the two DRD displays²⁶, and so only one DRD display was exogenously attended to in each trial. Additionally, one motion direction was always presented to the side in which exogenous attention was directed (attended location), and a different motion direction was always paired with the DRD display not exogenously attended (unattended location). The results showed no pre-/post-test performance improvement for task-irrelevant stimuli presented at the attended location, while TIPL was found for task-irrelevant stimuli presented at the unattended location, demonstrating that TIPL can be modulated by exogenous attention (Choi *et al.*, 2009).

1.7 ARE TASK-RELEVANT AND TASK-IRRELEVANT PERCEPTUAL LEARNING EFFECTS COMPARABLE?

In 2009, Seitz and Watanabe tried to compare the learning effects observed in task-relevant perceptual learning (TRPL) with those observed in task-irrelevant perceptual learning (TIPL). In order to make this comparison, the authors analysed learning slopes for both TRPL and TIPL studies. More specifically, they used: 1) the learning data of TRPL studies analysed in a review comparing the TRPL effect across 16 psychophysical studies (Fine & Jacobs, 2002); 2) the learning data of TIPL studies in which the d' measured in the pre-test ranged between 0.5 and 1²⁷, and in which the training lasted for 20 days at most²⁸. Seitz and Watanabe (2009) reported

²⁵ The direction of the coherently moving dots was different in the two DRD displays.

²⁶ The arrows served as an exogenous orienting cue; it has been demonstrated that an arrow can automatically orient attention toward the spatial location where the arrow-head points (Tipples, 2002).

²⁷ This inclusion criteria was also used in the review by Fine and Jacobs (2002), and corresponds to a performance of between 59.9%-68.7% correct responses in a binary task (Fine & Jacobs, 2002).

²⁸ See for example Watanabe *et al.*, 2001; Seitz & Watanabe, 2003; Seitz *et al.*, 2005; Nishina, Seitz, Kawato, & Watanabe, 2007; Tsushima *et al.*, 2008.

that: 1) the average value of learning slopes in TRPL studies was 0.173 (range 0.001–0.381); 2) the average value of learning slopes in TIPL studies was 0.179 (range 0.085–0.320). Taking these data into account, it would appear that the learning effects observed in TRPL and TIPL are indeed comparable; it should be pointed out, however, that this comparison is rather unsatisfactory, providing a mere indication of learning effect directions in TRPL and TIPL, because the authors have compared studies which have different procedures, stimuli and tasks, and above all, different training paradigms. TRPL training paradigms typically use a training that lasts from one to five days, while the training in TIPL training paradigms can last for 20 days or longer. Seitz and Watanabe (2009) stated that *“we are comparing TIPL to a select group of TRPL studies and that our analysis mostly shows that TIPL falls within the distribution of learning produced by TRPL, not that TIPL is equivalent to TRPL”* (Seitz & Watanabe, 2009, page 2608). In other words, they were aware that the aforementioned comparison between TRPL and TIPL did not allow them to conclude that the magnitude of learning effects in both lines of studies was equivalent, but they failed to mention the fact that to reach a comparable average value of the learning slopes, participants in TIPL studies have to train for much longer than in the TRPL studies, and this represents a crucial difference.

1.8 TASK-IRRELEVANT PERCEPTUAL LEARNING IN THE FRAMEWORK OF LEARNING MODELS

When we talk about task-irrelevant perceptual learning (TIPL), and more in general about perceptual learning, it is important to keep two aspects of the learning process quite distinct, and namely, when the learning occurs and what is learned. In other words, it is vital to make a clear distinction between the mechanisms that promote learning, and the stages of visual processing which are changed through learning.

This section contains a review of studies designed to clarify when visual perceptual learning occurs, and what is learned through visual perceptual learning, explaining the differences and the similarities between task-relevant perceptual learning (TRPL) and task-irrelevant perceptual learning (TIPL).

1.8.1 When does perceptual learning occur?

In the framework of TRPL studies, it has been shown that features or stimuli are learned when attention is directed towards those features/stimuli. In other words, attention plays an important role in TRPL because it is necessary for visual perceptual learning to occur (Shiu & Pashler, 1992; Ahissar & Hochstein, 1993; Schoups *et al.*, 2001). This is not true, on the other hand, in the case of TIPL, in which task-irrelevant stimuli (noise) are learned even when they are unattended (and sub-threshold), with the constraint that they have to be presented at behaviourally relevant points in time.

As previously shown (see paragraph 1.4), the two main mechanisms that promote TIPL are elicited: 1) by the primary task in which participants are engaged while being exposed to task-irrelevant stimuli (i.e., the successful recognition of a task-relevant stimulus promotes an internal reward mechanism, which in turn gives rise to the learning of the task-irrelevant stimulus temporally paired with the target occurrence, Seitz & Watanabe, 2003); 2) by external rewards (i.e., the temporal pairing between an external reward and the presentation of a task-irrelevant stimulus is sufficient to cause TIPL, Seitz *et al.*, 2009). It has been hypothesized that the aforementioned mechanisms which promote visual perceptual learning (i.e., attention in TRPL, and internal and external reward in TIPL) do not conflict with each other: instead, both contribute in a different but complementary way to the learning process. In TRPL, attention may serve to enhance (or to suppress) task-relevant stimuli, while in TIPL, the association between the presentation of task-irrelevant stimuli and the occurrence of a reward (internal or external) boosts the perception of stimuli which are initially inadequately processed.

1.8.2 What is learned in perceptual learning?

In literature, there is no consensus regarding the stage or the stages of visual processing that are changed through visual perceptual learning.

In the context of TRPL, three main models (early-stage, mid-stage and late-stage) have been proposed in an attempt to explain what is learned through visual perceptual learning: the difference between them has to do with the stage of visual processing and the brain areas in which learning is considered to occur. Each of these models is presented and explained below.

(a) EARLY-STAGE MODEL

In the early-stage model, TRPL is considered to be associated with changes in the early visual cortex areas (specifically in the following low-level visual areas: V1, V2 and V3)²⁹ (for example, Karni & Sagi, 1991; Karni & Sagi, 1993; Fahle & Edelman, 1993; Fahle, 1994; Crist, Kapadia, Westheimer, & Gilbert, 1997; Fahle, 2002; Fahle & Poggio, 2002; Xu, He, & Ooi, 2010; Xu, He, & Ooi, 2012; Choi & Watanabe, 2012).

This model was conceived subsequent to findings that visual perceptual learning is very specific for the trained feature (such as stimulus orientation: Fiorentini & Berardi, 1980; Poggio, Fahle, & Edelman, 1992; motion-direction: Ball & Sekuler, 1987; Watanabe *et al.*, 2002), for the trained eye (i.e., the performance improvement on a feature/stimulus trained in only one eye does not transfer to the other eye; for example, Karni & Sagi, 1991; Karni & Sagi, 1993; Fahle & Poggio, 2002), and for the trained spatial location (i.e., the performance improvement on a feature/stimulus trained in one spatial location of the visual field does not transfer to another spatial location; for example, Fiorentini & Berardi, 1980; Karni & Sagi, 1991; Fahle & Edelman, 1993; Ahissar & Hochstein 1997; Watanabe *et al.*, 2002)³⁰. Early visual cortex areas can account for these types of specificity (Hubel & Wiesel, 1968; Felleman & Van Essen, 1991). Moreover, studies in animal physiology reported evidences of V1 changes in connection to TRPL (Schoups *et al.*, 2001; Crist *et al.*, 2001; Hua *et al.*, 2010). Further evidence in support of the early-stage model is that an external response feedback³¹ is not necessary for visual perceptual learning to occur (Poggio *et al.*, 1992; Fahle *et al.*, 1995): this implies that the involvement of high-level visual areas is not required. In 1997, Ahissar and Hochstein

²⁹ These areas are involved in the processing of simple visual features such as orientation, contrast, and spatial frequency, and have smaller receptive fields compared to higher visual areas (Hubel & Wiesel 1968; Felleman & Van Essen, 1991).

³⁰ Fahle (1994) claimed that: *"The orientation specificity we found requires that the neurons that learn are orientation specific ... the fact that learning is mostly eye specific suggests that the neurons that learn are mostly monocular ... the position specificity of learning indicates that the underlying neuronal processes occur in a cortical area where position invariance has not yet been achieved. These results suggest Area V1 as the most probable candidate for learning of visual hyperacuity"* (Fahle, 1994, page 418).

³¹ It is common in visual perceptual learning studies to give to participants a feedback regarding the correctness of a response (external response feedback). Although it has been shown that giving a response feedback accelerates the learning process (Fahle & Edelman, 1993), it is not necessary for visual perceptual learning to occur (McKee & Westheimer, 1978).

demonstrated that there is a positive correlation between training task difficulty and specificity of visual perceptual learning (in their case, specificity for stimulus orientation and for stimulus spatial location). To be more precise, when the training task is easy, there is a transfer of learning across orientations and spatial locations, suggesting that learning occurs in high-level visual areas, where neurons receptive fields generalize across orientation and spatial location, whereas when the training task becomes more difficult, the learning specificity increases, suggesting that learning occurs in low-level visual areas, where neurons receptive fields are smaller and specific for orientation and spatial location (Ahissar & Hochstein, 1997).

Based on the aforementioned finding, the authors proposed their reverse hierarchical model in order to explain how visual perceptual learning occurs. This model postulates that visual perceptual learning is a top-down guided process (Ahissar & Hochstein, 1997; Ahissar & Hochstein, 2004; Ahissar, Nahum, Nelken, & Hochstein, 2009), which proceeds from higher cortical areas to early visual cortex areas³².

(b) MID-STAGE MODEL

In the mid-stage model, TRPL is considered to be associated with changes in the mid-level visual cortex areas (specifically in the following areas: V4, MT and V3A)³³ (for example, Doshier & Lu, 1998; Lu *et al.*, 2005; Petrov, Doshier, & Lu, 2005, 2006).

This model was conceived after it was observed that transfer of visual perceptual learning is possible under particular conditions. Liu (1999) trained participants to perform a motion discrimination task in which participants had to judge whether two sequentially presented

³² A functional magnetic resonance imaging (fMRI) study by Sigman and colleagues (2005) seems to corroborate the reverse hierarchical model. The authors trained participants in a visual search task (i.e., participants had to identify a T-shape target among distractors). The fMRI results showed a predominant activity of higher cortical areas at the beginning of the training, while at the end of the training, the prevalent activity was observed in the early visual cortex areas. This result seems to corroborate the hypothesis that learning is a top-down guided process.

³³ These areas are involved in the processing of visual stimuli more globally than the early visual cortex areas; for example, V4 is responsible of the processing of colour constancy (Zeki, 1993) and of the surface representation (Bouvier, Cardinal, & Engel, 2008), while the middle-temporal area (MT) and V3A respond to global motion (Braddick *et al.*, 2001; Koyama *et al.*, 2005).

motion stimuli have the same or different directions of a modest difficulty³⁴, and he found that visual perceptual learning can transfer to new (untrained) motion directions after training (Liu, 1999). This result seems to indicate that visual perceptual learning may occur in mid-level visual cortex areas, in which feature stimulus properties, such as direction, are less specific than in early visual cortex areas. This hypothesis has been corroborated in a study by Yang and Maunsell (2004), in which they examined how visual perceptual learning affects neuronal responses in the mid-level visual cortex area V4. The authors trained adult macaque monkeys in an orientation match-to-sample task (i.e., animals had to show two different behavioural responses depending on whether the two sequentially presented stimuli match or not) at a specific retinal location. The results showed that, after a prolonged training, the neuronal responses in V4 changed compared to those registered at the beginning of the experiment, demonstrating that visual perceptual learning can alter neuronal responses in a mid-level visual cortex area³⁵.

In order to account for these findings and to explain how visual perceptual learning occurs, Doshier and Lu proposed the reweighting model (RM) (Doshier & Lu 1998; Lu *et al.*, 2005; Petrov *et al.*, 2005, 2006). A brief explanation is useful here before I illustrate this model. As described in paragraph 1.2, human perceptual systems constantly receive a rich amount of information from the environment, and perceptual learning can be seen as the ability of those perceptual systems to select and become increasingly sensitive to important stimuli (Fahle & Poggio, 2002). We can consider the aforementioned important stimuli as signal, and all the other stimuli as external noise. Doshier and Lu (1998) have hypothesized that perceptual learning results in the ability to exclude external noise from the signal (Doshier & Lu, 1998). This view is confirmed by a lot of studies which have shown that the magnitude of learning is positively correlated with the increase in external noise-signal ratio (i.e., when signals are

³⁴ In studies which have found specificity of visual perceptual learning for the motion direction, the directional difference (meaning the difference in orientation between the two sequentially presented motion stimuli) traditionally used in motion discrimination tasks is 3° (i.e., the task is really difficult) (for example, Ball & Sekuler, 1982). In the study by Liu (1999), a directional difference of 8° was used, so as to obtain an easier condition of the motion discrimination task.

³⁵ The same research group has previously used the same experimental paradigm and it has reported no changes in V1 and V2 associated to visual perceptual learning (Ghose *et al.*, 2002).

embedded in noise, the magnitude of learning is greater) (Doshier & Lu, 1998, 1999; Gold, Bennett, & Sekuler, 1999; Li, Levi, & Klein, 2004). Moreover, Doshier and Lu (1998) have postulated that another mechanism plays a fundamental role in perceptual learning: the ability to reduce internal noise, which corresponds to an enhancement of the signal. In the RM, Doshier and Lu have suggested that visual perceptual learning operates to selective re-weight connections between V1 and a decision unit (i.e., the *locus* of the decision unit is in the mid-level visual areas), and that this process helps both to improve the filtering of external noise (by reducing irrelevant connections), and to reduce internal noise (by improving relevant connections). To conclude, in the RM the change associated with visual perceptual learning is in the connections between V1 and the mid visual cortex areas, and is not a change in the stimulus representation (i.e., a change in V1) (Doshier & Lu, 1998).

(c) LATE-STAGE MODEL

In the late-stage model, TRPL is considered to be associated with changes in the higher areas (specifically in the following high-level areas: lateral intraparietal sulcus (LIP), and dorsolateral prefrontal cortex (DLPFC))³⁶.

This model is based on two main findings. In 2008, Law and Gold trained rhesus monkeys on a motion direction discrimination task, while recording neuronal activity in the middle temporal area (MT) where the motion information is represented, and in the lateral intraparietal area (LIP) where the motion information is converted into a decision behaviour (a saccadic choice). The results showed a performance improvement after training, but the most intriguing finding was that this improvement was accompanied by a response change in the LIP neurons but not in the MT ones, indicating that visual perceptual learning determines changes in areas which are involved in visual decision processing (Law & Gold, 2008). It has also been shown that a complete transfer of visual perceptual learning can be observed between two distinct spatial locations of the visual field (i.e., location transfer) when a double-training procedure is used (Xiao *et al.*, 2008). In the study by Xiao and colleagues (2008),

³⁶ These areas are involved in the processing of visual stimuli in more cognitive manners: for example, it has been shown that the lateral intraparietal sulcus (LIP), and the dorsolateral prefrontal cortex (DLPFC) are involved in the visual decision process (Shadlen & Newsome, 1996; Heekeren, Marrett, Bandettini, & Ungerleider, 2004).

location transfer was enabled when an unrelated task was performed on task-irrelevant visual features/stimuli in the transfer location (meaning the location tested at the end of the experiment in order to evaluate location transfer). To be more specific, the authors trained participants on a feature (the contrast of Gabor patches) at one spatial location, and then had them undergo additional training on a task-irrelevant feature of the same stimulus (this time, the orientation of Gabor patches) in a second spatial location. The results showed a complete location transfer (Xiao *et al.*, 2008; for an example of transfer across different stimulus orientations, see Zhang, Xiao, Klein, Levi, & Yu, 2010), and further research indicated that a necessary condition for transfer of visual perceptual learning to occur is to perform a second task in the second spatial location for an adequate number of trials (Mastropasqua, Galliussi, Pascucci, & Turatto, 2015).

In order to account for these findings and explain how visual perceptual learning occurs, Xiao and colleagues (2008) built a model in which they postulated that TRPL is associated only with changes in higher areas. To be more precise, the authors suggested that the connections between high-level areas and locations in the visual field are normally inhibited, but can be reactivated by the performing of a second task (i.e., it is a double training paradigm), and this may account for the transfer of TRPL (Xiao *et al.*, 2008).

1.8.3 How to take account for task-irrelevant perceptual learning? The dual plasticity model

The aforementioned visual perceptual learning models account only for TRPL, without providing an explanation for TIPL.

In 2005, Seitz and Watanabe proposed the dual plasticity model (DPM) in order to explain TRPL as well as TIPL, postulating that these two types of visual perceptual learning share the same underlying principles. The expression *dual plasticity model* was used because according to the authors, two different types of plasticity exist: one feature-based and one task-based. Feature-based plasticity is the change occurring during training in the representation of either a task-relevant or task-irrelevant feature/stimulus presented in a certain spatial location, while task-based plasticity is the change occurring in the processing of the task performed during training. According to this model, TRPL is shaped by both types of plasticity, while in TIPL only feature-based plasticity occurs. This assumption is easily explained if we consider

that feature-based plasticity is enabled by reinforcement signals (internal or external reward) which are common in both TRPL and TIPL (i.e., exposure to a feature/stimulus and the simultaneous presentation of a reward is sufficient to trigger feature-based plasticity). Task-based plasticity, on the other hand, is enabled by active involvement in a trained task, which is typical of TRPL. For example, performing two different tasks (such as a detection and a discrimination task) on the same feature/stimulus, triggers two qualitatively different types of task-based plasticity (Seitz & Watanabe, 2005).

Moreover, the authors proposed that feature-based plasticity is associated with changes in the early- and mid-level visual cortex areas (where the trained feature/stimulus is mostly processed), while task-based plasticity is associated with changes also in the higher areas (Seitz & Watanabe, 2005). In order to test this hypothesis, and also the validity of the DPM, Shibata and colleagues (2016) designed a brain imaging experimental paradigm for measuring the neural response changes associated with feature- and task-based plasticity. The authors used a three-stage experimental paradigm (pre-test, training and post-test), in which participants had to perform a task (global motion detection) in two different test conditions (active and passive), and they determined the pre-/post-test changes associated with feature- and task-based plasticity using functional magnetic resonance imaging. The results confirmed the validity of the DPM by showing that both types of plasticity did indeed occur during visual perceptual learning. The authors showed that different brain areas are involved in feature- and task-based plasticity; pre-/post-test changes in V3A (i.e., mid-level area) were observed in both the active and passive test conditions, demonstrating that this area is involved in feature-based plasticity, while pre-/post-test changes in V1 (i.e., low-level area) and in the intraparietal sulcus (i.e., higher area), were observed only in the active-test conditions, suggesting that task-based plasticity is reflected in changes also in high-level areas (Shibata *et al.*, 2016).

In conclusion, the DPM is still only a rough model, because it does not provide a detailed description of the mechanisms underlying feature- and task-based plasticity, and the links between the two. It does, however, account for the majority of recent TRPL and TIPL experimental results, and also for the imaging evidence which has shown that TRPL and TIPL involve changes at multiple stages in information processing and thus in different brain areas (also beyond the visual cortex).

1.9 WHAT IS THE FUNCTION OF TASK-IRRELEVANT PERCEPTUAL LEARNING?

Several studies have shown that the brain mechanisms of perception and learning, which have been shaped by evolution, work extremely well in most situations, but they are not always beneficial (Chun & Marois, 2002; Seitz *et al.*, 2005b). As described above, task-irrelevant perceptual learning (TIPL) enables the learning of task-irrelevant, unattended and sub-threshold stimuli presented at behaviourally relevant points in times (i.e., with the occurrence of internal or external rewards; Seitz *et al.*, 2003; Seitz *et al.*, 2009). In order to understand the function of TIPL, the crucial point is that this learning mechanism operates at relevant points in time, implying that TIPL does not occur in every situation.

Perhaps the function of TIPL, in terms of its ecological validity, can be better understood if we think about this learning mechanism outside an artificial laboratory context. Typically, in a natural environment, a reward (and more generally, a behaviourally relevant event such as a punishment) is given because it serves to enhance learning. For example, an animal might be forced to search for food (target) in a new place, because food is scarce in the place where the animal usually searches for it. If the animal finds the food (reward) in the new place A, but not in the new place B, he learns that he has to go to place A to find the food. However, from the animal's point of view, what is important to learn is not only the aforementioned general rule (namely, go to place A to find food), but also the important aspects of the environment that are predictive or co-vary with the reward (food), because becoming more sensitive to the features of the environment (i.e., the task-irrelevant features) where the animal can find the reward, may lead it to find the reward faster and more easily (Schultz, 2000; Dalley *et al.*, 2001; Dayan & Balleine, 2002; Doya, Samejima, Katagiri, & Kawato, 2002).

CHAPTER 2

Task-irrelevant perceptual learning study

2.1 CHAPTER OVERVIEW

This chapter presents two experiments designed to further explore the phenomenon of task-irrelevant perceptual learning (TIPL). These experiments were conducted at the Laboratory of Psychophysics (LPSY) at the Ecole Polytechnique Fédérale de Lausanne (EPFL), where I spent six months under the co-supervision of Professor Michael Herzog. After a brief introduction which sets out the theoretical framework needed for a clear understanding of the topic under investigation, the two experiments are then described in detail. In each case, the aim, method, data analysis and results are illustrated separately. By way of conclusion, a brief discussion is presented.

2.2 INTRODUCTION

The mechanisms underlying visual perceptual learning are one of the main subjects of debate in visual perception. For a time, task-relevance, attention, and awareness were thought necessary for perceptual learning (Shiu & Pashler, 1992; Ahissar & Hochstein, 1993), but this view was then challenged by the discovery of task-irrelevant perceptual learning (TIPL) (Watanabe *et al.*, 2001). This ground-breaking study showed for the first time that visual perceptual learning can occur for task-irrelevant, unattended and even sub-threshold stimuli. A series of subsequent studies contributed to provide further evidence of TIPL, especially but not exclusively (for example, Leclercq & Seitz, 2011, 2012a, 2012b, 2012c) in the context of low-level perceptual learning (for a review, see Watanabe & Sasaki, 2015).

As described in Chapter 1, the two views about the constraints of perceptual learning are not as conflicting as they may appear, and can be satisfactorily reconciled by analysing the

properties of the task-irrelevant features/stimuli used in the experiments. In the first line of research (Shiu & Pashler, 1992; Ahissar & Hochstein, 1993), the task-irrelevant features proven not to have been learned after training were presented at a supra-threshold level, while in the TIPL studies (Watanabe *et al.*, 2001; Seitz *et al.*, 2003), which showed perceptual learning for task-irrelevant stimuli after training, the task-irrelevant stimuli were presented at a sub-threshold level.

Another difference between studies that did not find task-irrelevant perceptual learning and those that did lies in the stimuli used during the training. For example, in Shiu and Pashler (1992), the authors used only one spatially attended stimulus (a pair of straight lines) and they evaluated perceptual learning for two different features of that stimulus, one characterized as task-relevant (i.e., the feature on which participants performed the task; brightness) and the other as task-irrelevant (i.e., the feature to which participants were only exposed, but not required to perform any task on; orientation). In the study by Watanabe and colleagues (2001), on the other hand, two different stimuli were used, presented in two different spatial locations: while the task-relevant stimulus (letter) was presented in the fovea, the task-irrelevant stimulus (motion) was presented in the peripheral visual field.

It is quite possible that Shiu and Pashler (1992) found no evidence of TIPL not because of the experimental paradigm used, but because the task-irrelevant feature they used in their experiment was presented at a supra-threshold level. Tsushima and colleagues (2008) demonstrated that a necessary condition for TIPL to occur is para- or sub-threshold presentation of the task-irrelevant features/stimuli. They argued that task-irrelevant stimuli presented at sub- or para-threshold level fail to be detected by the attentional system and are therefore learned. When task-irrelevant stimuli are presented at a supra-threshold level, on the other hand, they are detected and suppressed by the attentional system, and therefore not learned (attention-based suppression hypothesis; Tsushima *et al.*, 2008; Tsushima & Watanabe, 2009; Roelfsema *et al.*, 2010). It can be therefore hypothesized that in the study by Shiu and Pashler (1992) the task-irrelevant feature was not learned because the attentional system inhibited the learning of that feature, which was supra-threshold.

The present study attempts to deepen the understanding of the mechanisms underlying visual perceptual learning by using an experimental paradigm combining a paradigm similar to that used in Shiu and Pashler (1992) with the one used in the first TIPL study by Watanabe and

colleagues (2001). To be more precise, one stimulus (a 3-dot vertical pattern) presented in a fixed spatial location (fovea) was used for the entire duration of the experiment (similar to Shiu and Pashler, 1992), and a three-stage procedure consisting of pre-test, training, and post-test was used (similar to Watanabe and colleagues, 2001). Participants were trained for six days to perform a discrimination task on a specific feature (luminance) of the 3-dot vertical pattern, while they were simultaneously exposed to a task-irrelevant and sub-threshold feature (horizontal offset) of the same stimulus. The general aim of the two experiments here described was to investigate whether TIPL can occur as result of mere exposure to a task-irrelevant and sub-threshold feature (horizontal offset) of a stimulus, even when during training participants attend and perform a task on a different feature of a homologous stimulus.

2.3 EXPERIMENT 1

2.3.1 Aim and expected results

The aim of the experiment was twofold: (1) to test whether TIPL occurs by the exposure to a task-irrelevant and sub-threshold feature (horizontal offset) of a stimulus when the training stimuli are homologous to those in the pre- and post-test; (2) to investigate the specificity of TIPL by comparing performance in two different tasks: one for which participants received a specific training (Vernier task) and the other for which participants did not receive it (bisection task).

I expected to find: (1) a significant improvement after training in the Vernier task because the training was specifically designed to improve performance in the Vernier task; (2) a larger improvement after training in the Vernier than in the bisection task (performance in the bisection task might benefit from repeating testing, but less than Vernier task because training was not specific to the bisection task).

2.3.2 Methods

(a) Participants

Twenty naïve students from the Ecole Polytechnique Fédérale de Lausanne (EPFL) (5 females; age range: 19-25) voluntarily participated in the experiment in exchange for money compensation (20 Swiss francs, CHF, per hour). The sample size exceeds other published studies which have successfully demonstrated significant TIPL effects (for example, Watanabe *et al.*, 2001).

All participants had normal or corrected-to-normal visual acuity measured using the Acuity task of the adaptive computerized Freiburg Visual Acuity Test (FrACT)³⁷ (Bach, 1996) (i.e., participants needed to obtain a score above 1.0 in at least one eye³⁸).

Written informed consent was obtained for each participant before the beginning of the experiment. Procedures were conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) and approved by the local ethics committee.

(b) General setup

The experiment took place in a dimly illuminated (approx. 0.5 lux) room. Visual stimuli were presented in the centre of a X-Y monitor (Tektronix 608 X-Y display with P11 phosphor, blue), driven by a custom-made 16-bit DA converter with a dot rate of 1 Mdots/s³⁹. Participants sat at a distance of 2m from the monitor and their heads were stabilized with a chinrest with a forehead bar.

³⁷ In each trial of the Acuity task of the Freiburg Visual Acuity Test (FrACT), an optotype (Landolt C) is presented in one of eight orientations. Participants have to press one of eight buttons according to the optotype direction. The procedure starts by presenting participants with a trial in which an easy to recognize optotype (because of its dimension) appeared on the screen; in the following trials, depending on the correctness of participants' responses, a smaller (in case of correct response) or a bigger (in case of wrong response) optotype is presented. After an established number of trials, participant's visual acuity is determined (Bach, 1996).

³⁸ A score above 1.0 in the FrACT corresponds to a Snellen fraction of 20/20.

³⁹ The dot pitch (i.e., the distance between the dots making up a line or a patch) was set at 300µm.

(c) Stimuli and tasks

The stimulus was a 3-dot pattern. The outer dots were arranged along the vertical axis. The standard luminance of the dots was 80 cd/m^2 (luminance was measured with a Minolta LS-100 luminance meter) and the distance of the dots from each other was $1000''$ (arcsec).

Three binary forced choice tasks were used: a Vernier task, a bisection task and a luminance discrimination task.

In the Vernier task, the dot placed in the middle of the 3-dot vertical pattern (middle dot) was offset in the horizontal direction, i.e., to the left or to the right of the imaginary vertical line that connected the outer dots. There were thus two configurations of the Vernier stimulus: left offset and right offset (Figure 2.1). Participants had to discriminate whether the middle dot was offset to either the left or the right.

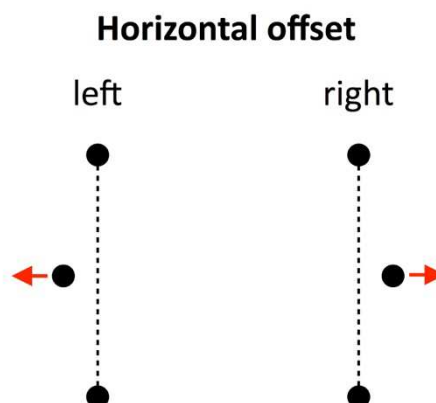


Figure 2.1 - Schematic of the two configurations of the Vernier stimulus. A left offset is represented on the left; a right offset is represented on the right.

In the bisection task, the middle dot was offset in the vertical direction, i.e., it was closer to the upper or to the lower dot. There were thus two configurations of the bisection stimulus: upward offset and downward offset (Figure 2.2). Participants had to discriminate to which of the outer dots the middle dot was closer.

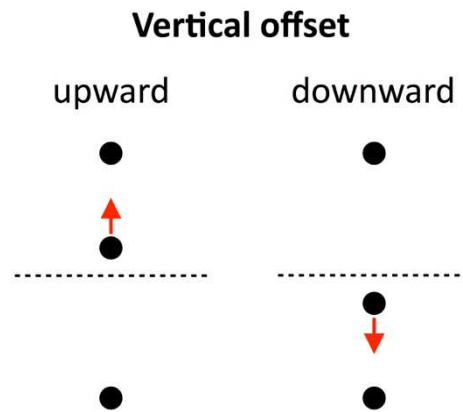


Figure 2.2 - Schematic of the two configurations of the bisection stimulus. An upward offset is represented on the left; a downward offset is represented on the right.

In the luminance discrimination task, the dots of the 3-dot vertical pattern had a different luminance from each other: the luminance of the middle dot was maintained at 80 cd/m², while one of the outer dots had a higher and the other a lower luminance than the middle dot. Participants had to discriminate which of the outer dots was brighter.

In each trial of the three aforementioned tasks, a fixation screen (indicating the four corners of the screen and a central fixation mark) was presented for 300 ms. Then, after a blank screen of 200 ms, the 3-dot vertical pattern was presented at the centre of the display for 150 ms. The next trial followed after participant's response and the response timeout was set at 5 s (Figure 2.3).

For all tasks, participants gave their responses by pressing the appropriate one of two push buttons and they received an auditory feedback for correct answers.

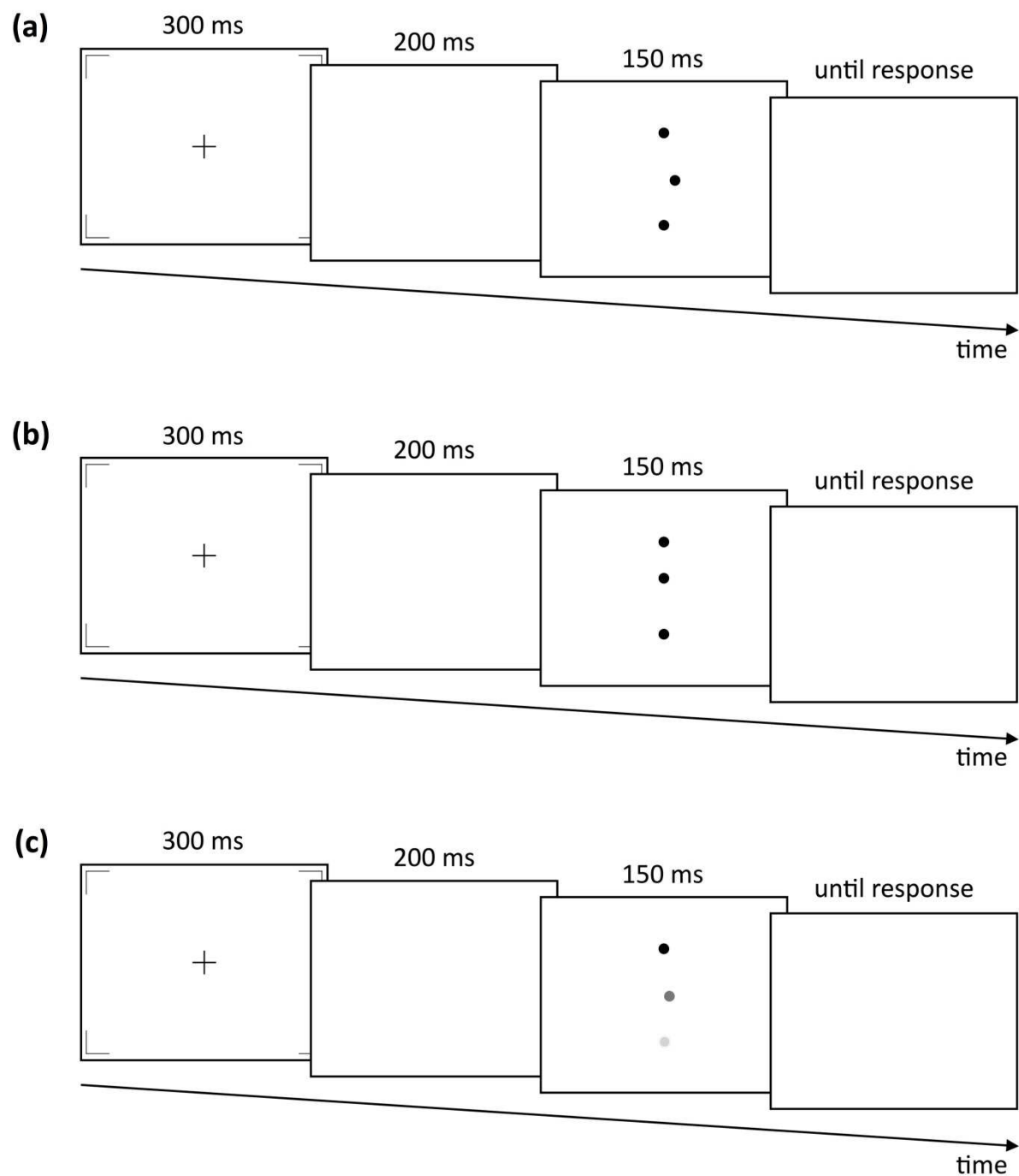


Figure 2.3 - Schematic of a single task trial used in Experiment 1. In each task, participants were sequentially presented with a fixation screen (300 ms), with a blank screen (200 ms), with a test screen (150 ms) and with a response (blank) screen. Panel (a): example of a Vernier task trial in which the middle dot is offset to the right. Panel (b): example of a bisection task trial in which the middle dot is closer to the upper dot. Panel (c): example of a luminance discrimination task in which the lower dot was brighter than the upper dot.

(d) General procedure

The experiment lasted 8 consecutive days (8 experimental sessions): on day 1 participants underwent a brief familiarization phase and a pre-test (duration: approx. 1 hour); from day 2 to day 7 they underwent training (approx. 45 minutes/day); on day 8 they underwent a post-test (approx. 35 minutes) (Figure 2.4). On each day, before starting the experimental session, participants were provided with both written and oral instructions.

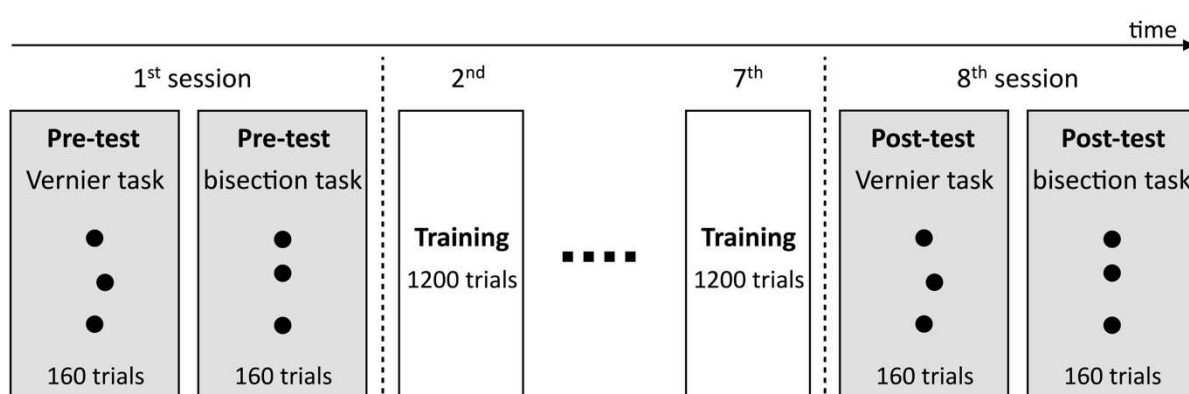


Figure 2.4 - Schematic of the 3-stage procedure employed in Experiment 1. Participants performed 6 training sessions. Pre- and post-test were administered in the first and the last session.

FAMILIARIZATION PHASE

Before starting the experiment, participants were familiarized with the psychophysical setup by performing 80 trials of an oblique (45° given the vertical is 0°) Vernier task. The dots were placed at a distance of $2000''$ from each other. Participants had to indicate whether the middle dot was offset to the left-up or right-down of the imaginary oblique line that connected the outer dots, by pressing a left or a right push button, respectively.

PRE-TEST

Participants performed a Vernier and a bisection task (two blocks of 80 trials each).

The order in which participants performed the two tasks was randomized across participants. The offset direction (i.e., in the Vernier task the offset direction could be left or right; in the bisection task the offset direction could be upward or downward) was presented in random order within each block with the constraint that the same offset direction was not presented more than four times in a row.

The discrimination thresholds (of 75% correct responses over 80 trials) were measured by an adaptive staircase method and maximum likelihood estimation of the parameters of the psychometric function (parameter estimation by sequential tracking [PEST]; starting value: 100''; PEST start step size: 3; PEST WALD constant: 1.5; Taylor & Creelman, 1967).

For the Vernier task, two discrimination thresholds were measured and the arithmetical mean of the two thresholds was then computed in order to obtain only one pre-test discrimination threshold called *Vernier PRE threshold*. The same procedure was employed to calculate the *bisection PRE threshold* relative to the performance in the bisection task.

TRAINING

First, before starting the training, for each participant, the luminance discrimination threshold (of 75% correct responses over 80 trials) was measured twice by an adaptive staircase method and maximum likelihood estimation of the parameters of the psychometric function (parameter estimation by sequential tracking [PEST]; luminance difference starting value: 38% of the luminance of the middle dot (80 cd/m^2); PEST start step size: 3; PEST WALD constant: 1.5; Taylor & Creelman, 1967). The lowest luminance discrimination threshold of the two was then used for the entire training to test participants with the method of constant stimuli (MCS)⁴⁰.

The training lasted six days: on each day participants performed 15 blocks of 80 trials of the luminance discrimination task.

⁴⁰ The method of constant stimuli (MCS) was developed by Gustav Fechner. Typically, it consists in repeatedly presenting the participant with a set of fixed stimuli. In the present experiment, only one fixed luminance difference value (corresponding to the lowest luminance discrimination threshold obtained in the preliminary measurements) was used to test participants for the entire training. This procedure was adopted in order to prevent the luminance discrimination task to be extremely difficult or easy to perform.

In each training trial, the middle dot was offset to the left or to the right with respect to the vertically arranged outer dots (horizontal offset) and the offset direction (left or right) was randomized across trials. The presence of the horizontal offset was the task-irrelevant feature of the stimulus, because in the luminance discrimination task, the task-relevant feature was the luminance of the outer dots. Moreover, this training was specifically designed to investigate the potential improvement after training in the Vernier task, because participants were exposed to an offset in the horizontal direction, as in the Vernier task.

The value of the horizontal offset was adjusted individually in order to be sub-threshold thus imperceptible for the participant. The sub-threshold was obtained by dividing the lowest Vernier discrimination threshold measured in the pre-test by a factor of 3. In order to verify that the horizontal offset value was effectively sub-threshold, the participant was tested in an additional block of 80 trials of the Vernier task with that horizontal offset value under the same conditions described for the pre-test, except that this time the MCS was employed (only one horizontal offset value was used). The d' was measured (Macmillan & Creelman, 2005) and if it was below 0.50 the horizontal offset value was considered effectively sub-threshold and it was used during the entire training. If the d' was above 0.50, the sub-threshold was recalculated by dividing the initial lowest discrimination threshold by a factor of 4 (and the participant was retested with the MCS as before). The same procedure was repeated for the bisection task to control for practice effects, although the sub-threshold offset value originated from the lowest discrimination threshold relative to the bisection task was not used during training.

POST-TEST

Participants performed a Vernier and a bisection task (two blocks of 80 trials each) under the same conditions described for the pre-test. As in the pre-test, for the Vernier task, two discrimination thresholds were measured and then averaged in order to obtain one post-test discrimination threshold called *Vernier POST threshold*. The same procedure was employed to calculate the *bisection POST threshold* relative to the performance in the bisection task.

2.3.3 Data analysis

To determine whether there was learning in the luminance discrimination task across the six training sessions, for each participant, first the d' relative to each training session was estimated, secondly individual training slopes were computed. Quantitative training data are presented as average training slope $\pm$ standard error of the mean (sem). Results were analysed for statistically significant differences by comparing training slopes against 0.

To determine whether post-test performance differed from pre-test performance and to compare participants' performances in the two tasks (Vernier and bisection task), for each participant, the *pre-post change* (dependent measure) computed as $100 * [(PRE \text{ threshold} - POST \text{ threshold}) / PRE \text{ threshold}]$ was calculated separately for the Vernier and the bisection task. The abovementioned formula normalized the pre-post change with respect to the expected positive difference between pre- and post-test discrimination thresholds. Quantitative data are presented as average pre-post change (%) $\pm$ sem. Results were analysed for statistically significant differences by using the following planned comparisons: Vernier pre-post change against 0, bisection pre-post change against 0 and Vernier pre-post change against bisection pre-post change.

2.3.4 Results and discussion

Learning was significant in the luminance discrimination task across the six training sessions (0.046 ± 0.013 ; two-tailed one sample t-test, $t[19] = 3.399$, $p = 0.003$), indicating that participants complied with the instructions to attend to the feature luminance of the dots (for individual data, see Supplemental Materials 1, Table S1.1).

The average pre-post change across participants was $20.5 \pm 5.0 \%$ and $1.9 \pm 9.0 \%$ respectively in the Vernier and the bisection task (Figure 2.5; for individual data, see Supplemental Materials 1, Table S1.2 and Table S1.3).

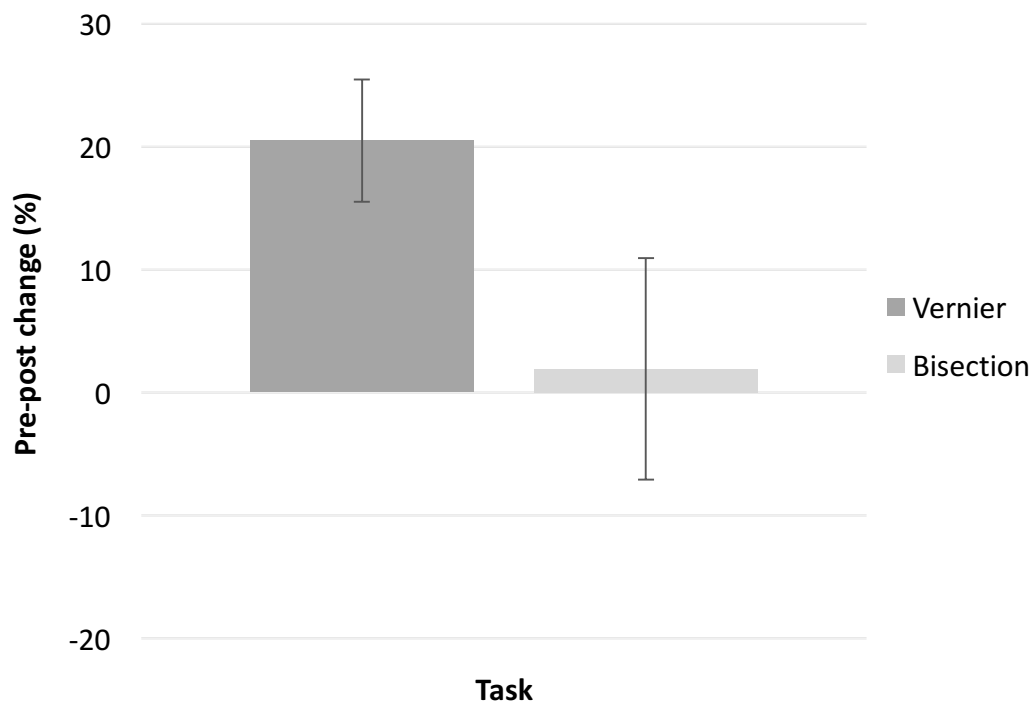


Figure 2.5 - Pre-post changes (%) in Vernier and bisection tasks (Experiment 1). The average pre-post change in the Vernier task was 20.5 ± 5.0 % (depicted in dark grey); the average pre-post change in the bisection task was 1.9 ± 9.0 % (depicted in light grey). Error bars represent the standard error of the mean (sem).

First, I tested whether pre-post changes observed in the Vernier task were significantly higher than chance by testing those values against zero. The results showed a significant pre-post change in the Vernier task (two-tailed one sample t-test, $t[19] = 4.118$, $p = 0.001$). Moreover, I repeated the same analysis for the bisection task founding no pre-post change (two-tailed one sample t-test, $t[19] = 0.213$, $p = 0.834$).

Secondly, I tested the unidirectional hypothesis that participants should show a larger pre-post change in the Vernier task (a task for which they received a specific training) than in the bisection task (a task for which they did not receive a specific training) by testing pre-post changes observed in the Vernier task against pre-post changes observed in the bisection task. As expected, a larger pre-post change was found in the Vernier task (one-tailed paired t-test, $t[19] = 1.932$, $p = 0.034$).

Taken together, the results seem to corroborate the hypothesis that the exposure to a task-irrelevant and sub-threshold horizontal offset during training yields perceptual learning, even when the training stimuli are homologous to those in pre- and post-test. Moreover, TIPL produced by the exposure to the horizontal offset during training seems to be task-specific because it does not transfer to another task (the bisection task) performed on the same stimulus.

However, it is not possible to rule out the possibility that other factors rather than the presence of the horizontal offset during training might account for the aforementioned results. For example, during training the three dots did not have the same luminance: one of the outer dot had a higher and the other a lower luminance than the middle dot. Phenomena of spatial pooling derived from luminance differences were previously reported with Vernier (Westheimer & McKee, 1977; Badcock & Westheimer, 1985), bisection (Grzeczowski, Tartaglia, Mast & Herzog, 2015), and other stimuli (Morgan, Ward & Cleary, 1994; Whitaker, McGraw, Pacey & Barrett, 1996; Bulatov, Bulatova & Surkys, 2012): one possibility is that the pattern of results observed in the present experiment might be influenced by the difference in luminance between the three dots. This is why I decided to conduct a second experiment (Experiment 2).

2.4 EXPERIMENT 2

2.4.1 Aim and expected results

Experiment 2 was conducted after having observed the results of Experiment 1.

In Experiment 2, the middle dot was perfectly aligned with the vertically arranged outer dots (no horizontal offset) and it was placed at an equal distance from the upper and the lower dot (no vertical offset). The difference between Experiment 1 and Experiment 2 was thus just the presence/absence of the horizontal offset. If the presence of the horizontal offset during training was a necessary condition for obtaining the results observed in Experiment 1, then its absence should produce a different pattern of results in Experiment 2 (namely, no pre-post change in either the Vernier or the bisection task, no difference in pre-post changes between the Vernier and the bisection task). Replicating in Experiment 2 the same pattern of results of

the Experiment 1, on the other hand, would falsify the conclusions of Experiment 1.

2.4.2 Methods

(a) Participants

Twenty⁴¹ naïve students from the Ecole Polytechnique Fédérale de Lausanne (EPFL) (8 females; age range: 19-26) voluntarily participated in the experiment in exchange for money compensation (20 CHF per hour). All participants had normal or corrected-to-normal visual acuity measured using the Acuity task of the adaptive computerized Freiburg Visual Acuity Test (FrACT) (Bach, 1996) (participants needed to obtain a score above 1.0 in at least one eye). Written informed consent was obtained for each participant before the beginning of the experiment. Procedures were conducted in accordance with the Declaration of Helsinki and approved by the local ethics committee.

(b) General setup, stimuli and tasks

The general setup, stimuli and tasks were the same as in Experiment 1.

(c) General procedure

The general procedure was the same as in Experiment 1, except that participants were not exposed to the task-irrelevant and sub-threshold feature used in Experiment 1 (the horizontal offset).

To be more precise, on each day of the 6-day training participants performed 15 blocks of 80 trials of the luminance discrimination task as in Experiment 1, but this time in each trial of the luminance discrimination task the middle dot was not offset, i.e., the middle dot was perfectly aligned with the vertically arranged outer dots (no horizontal offset) and it was placed at an equal distance from the upper and the lower dot (no vertical offset). In Experiment 2 the

⁴¹ As in Experiment 1, the sample size exceeds other published studies which have successfully demonstrated significant TIPL effects (for example, Watanabe *et al.*, 2001).

training was thus generic and not specifically designed to improve performance in either the Vernier or the bisection task.

It should be pointed out that the sub-threshold offset value was calculated both for the Vernier and the bisection task, although it was not used in this experiment, in order to maintain an identical procedure to that used in Experiment 1 (except for the presence/absence of the horizontal offset during training).

2.4.3 Data analysis

As in Experiment 1: (1) training: individual training slopes were computed. Quantitative training data are presented as average training slope $\pm$ sem and results were analysed for statistically significant differences by comparing training slopes against 0; (2) test: individual *pre-post change* (dependent measure) computed as $100 * [(PRE \text{ threshold} - POST \text{ threshold}) / PRE \text{ threshold}]$ was calculated separately for the Vernier and the bisection task. Quantitative data are presented as average pre-post change (%) $\pm$ sem. Results were analysed for statistically significant differences by using the following planned comparisons: Vernier pre-post change against 0, bisection pre-post change against 0 and Vernier pre-post change against bisection pre-post change.

2.4.4 Results and discussion

Learning was significant in the luminance discrimination task across the six training sessions (0.058 ± 0.014 ; two-tailed one sample t-test, $t[19] = 4.147$, $p = 0.001$), indicating that participants complied with the instructions to attend to the feature luminance of the dots (for individual data, see Supplemental Materials 2, Table S2.1).

The average pre-post change across participants was $-2.6 \pm 11.4 \%$ and $7.4 \pm 4.9 \%$ respectively in the Vernier and the bisection task (Figure 2.6; for individual data, see Supplemental Materials 2, Table S2.2 and Table S2.3).

In order to test the hypothesis that other factors rather than the presence of the horizontal offset during training have determined the results of Experiment 1, I conducted the same analysis as in Experiment 1.

First, I tested whether pre-post changes observed in the Vernier task were significantly higher than chance founding no pre-post change (-2.6 ± 11.4 %; two-tailed one sample t-test, $t[19] = -0.228$, $p = 0.822$). Moreover, I found no pre-post change also in the bisection task (7.4 ± 4.9 %; two-tailed one sample t-test, $t[19] = 1.499$, $p = 0.150$).

Secondly, I compared participants' pre-post changes observed in the Vernier task against pre-post changes observed in the bisection task founding no difference (two-tailed paired-samples t-test, $t[19] = -0.740$, $p = 0.469$).

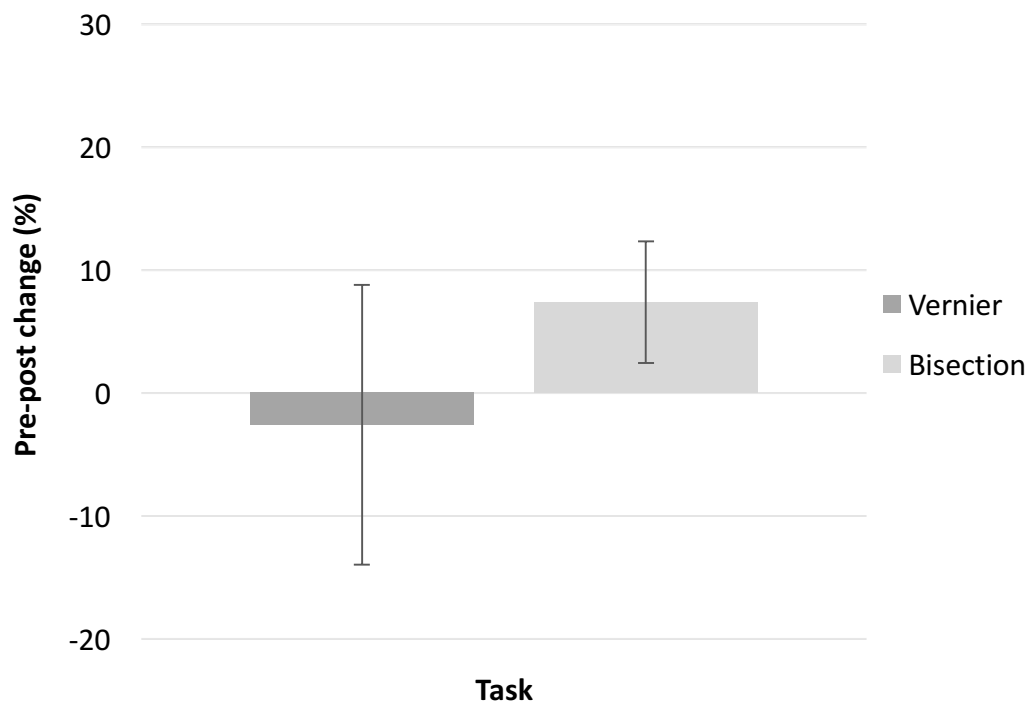


Figure 2.6 - Pre-post changes (%) in Vernier and bisection tasks (Experiment 2). The average pre-post change in the Vernier task was -2.6 ± 11.4 % (depicted in dark grey); the average pre-post change in the bisection task was 7.4 ± 4.9 % (depicted in light grey). Error bars represent the standard error of the mean (sem).

Taken together, the results of Experiment 2 did not falsify the conclusions of Experiment 1 because I did not replicate in the present experiment the same pattern of results of

Experiment 1 (i.e., in Experiment 2 I found no evidence of TIPL in either the Vernier or the bisection task, and no difference in performance between the two tasks). Consequently, I rejected the hypothesis that other factors rather than the presence of the horizontal offset during training have determined the results of Experiment 1.

2.5 GENERAL DISCUSSION

The discovery of task-irrelevant perceptual learning (TIPL), occurring for task-irrelevant and sub-threshold stimuli presented at an unattended, peripheral location (Watanabe *et al.*, 2001), has challenged the idea that task-relevance, awareness and attention are necessary for visual perceptual learning of a specific feature/stimulus to be observed (Shiu & Pashler, 1992; Ahissar & Hochstein, 1993; Schoups *et al.*, 2001).

As shown in Chapter 1, there were a number of methodological differences in those studies which did or did not find TIPL: for example, the number and the spatial arrangement of the stimuli used during training differed. Another important distinction had to do with the visibility properties of the task-irrelevant stimuli: for example, in the study by Shiu and Pashler (1992), which found no evidence of TIPL, the task-irrelevant feature was presented at a supra-threshold level, while in Watanabe and colleagues (2001), which did find evidence of TIPL, the task-irrelevant stimulus was presented at a sub-threshold level. Taking into account later studies which indicated that the attentional system inhibits the learning of task-irrelevant stimuli when those stimuli are presented at a supra-threshold level, while failing to detect and to suppress task-irrelevant stimuli presented at a para- or sub-threshold level (Tsushima *et al.*, 2008; Tsushima & Watanabe, 2009; Roelfsema *et al.*, 2010), it may be hypothesized that the main reason why some studies did not show TIPL is that they presented the task-irrelevant feature at a supra-threshold level (Shiu & Pashler, 1992).

In the study here described, I tested whether a task-irrelevant feature (horizontal offset) presented at a sub-threshold level is learned when, in the course of training, participants attend and perform a task on a different feature (luminance) of a homologous stimulus (a 3-dot vertical pattern). In order to address this topic, I used an experimental paradigm divided into three sequential stages (pre-test, training, post-test), similar to Watanabe and colleagues

(2001), in which only one stimulus was used during both tests and training, similar to Shiu and Pashler (1992).

In Experiment 1, the task performed by participants during the pre- and post-tests consisted of a judgment regarding the position of the middle dot of the 3-dot vertical pattern, which could be offset either in the horizontal direction (to the left or right) with respect to the vertically arranged outer dots (Vernier task) or in the vertical direction (upwards or downwards), hence closer to the upper or lower dot (bisection task). During training, the task consisted of a judgment regarding the luminance of the outer dots of the 3-dot vertical pattern. Luminance was thus the task-relevant feature used during training. While performing the training task, participants were also exposed to a horizontal offset: in each training trial, the middle dot was offset in the horizontal direction to an extent below the participants' thresholds of visibility. The horizontal offset was the task-irrelevant feature used during training and was thus presented at a sub-threshold level. In order to investigate whether TIPL occurred, the thresholds of discrimination for both the Vernier and the bisection task were measured, and then a pre-post performance index (named pre-post change) was computed. There was a significant improvement after training in the Vernier task, but no improvement in the bisection task. Moreover, the improvement after training observed in the Vernier task differed significantly from the one observed in the bisection task. Taken together, these results would seem to corroborate the hypothesis that TIPL can occur even when the training stimuli are homologous to those in pre- and post-test. They also would seem to indicate that TIPL is a task-specific learning mechanism because learning does not transfer to another task (the bisection task) performed on the same stimulus.

However, it was not possible to exclusively attribute the results of Experiment 1 to the mere exposure to the task-irrelevant and sub-threshold horizontal offset during training: other factors rather than the presence of the horizontal offset might account for the above-mentioned results. In order to rule out alternative explanations, a second experiment, named Experiment 2, was conducted.

Experiment 2 used the same procedure as Experiment 1, except that participants were not exposed to a (sub-threshold) horizontal offset during training: in each training trial, the middle dot was aligned with the outer dots along the vertical axis, and was placed at an equal distance from the upper and the lower dot. The only difference between Experiment 1 and Experiment

2 was therefore the presence/absence of the sub-threshold horizontal offset during training. After Experiment 2 was completed, the same analysis was performed as in Experiment 1 and a different pattern of results emerged: the participants showed no improvement after training in either the Vernier or the bisection task (and there was no difference in the pre-post change between the two tasks). In other words, Experiment 2 did not falsify the conclusions of Experiment 1 because the results of the two experiments did not match.

As previously stated, the only difference between the two experiments was the presence/absence of the horizontal offset during training: bearing in mind that a significant improvement after training in the Vernier task was found only in Experiment 1, in which participants were exposed to the horizontal offset during training, the pattern of results observed in Experiment 1 may reasonably be attributed to the presence of the horizontal offset during training.

In conclusion, the present study provides further evidence about the phenomenon of TIPL by showing that it occurs for a task-irrelevant and sub-threshold feature of a stimulus, despite the fact that during training, participants are engaged in performing a task on a different feature of a homologous stimulus. A further interesting finding was that the visual perceptual learning yielded by the task-irrelevant and sub-threshold feature is task-specific, because it occurs only in the task for which participants received a specific training, and is not transferred to another task performed on the same stimulus.

CHAPTER 3

Fast task-irrelevant perceptual learning

3.1 CHAPTER OVERVIEW

In this chapter, the phenomenon of fast task-irrelevant perceptual learning (fast-TIPL) is illustrated. After outlining the main difference between TIPL and fast-TIPL, the first demonstration of fast-TIPL is described in detail, with a few remarks on the use of the expression *fast-TIPL*. Then the constraints necessary for fast-TIPL to occur are listed. Lastly, in order to understand how fast-TIPL occurs, the attentional boost effect is explained.

3.2 FAST TASK-IRRELEVANT PERCEPTUAL LEARNING

Chapter 1 gave a description of the phenomenon of task-irrelevant perceptual learning (TIPL), highlighting the constraints necessary for TIPL to occur. To recapitulate briefly, TIPL is a type of perceptual learning which occurs for stimuli which have no task-relevance, which are unattended and sub-threshold, but which are presented at behaviourally relevant points in time (for a review, see Watanabe & Sasaki, 2015). It must be stressed that the expression *relevant points in time* refers to the occurrence of internal (Seitz & Watanabe, 2003) or external rewards (Seitz *et al.*, 2009). The initial goal of TIPL studies was to demonstrate that visual perceptual learning can occur in the absence of attention (Watanabe *et al.*, 2001), challenging the common view that learning a stimulus is possible only when attention is directed towards that stimulus (Shiu & Pashler, 1992; Ahissar & Hochstein, 1993; Schoups *et al.*, 2001). However, advances in TIPL research made it clear that rewards (internal and external) play an important role in TIPL, thereby making the TIPL experimental paradigm an important tool for a better understanding of how the interplay between attention and reward gates the learning of task-irrelevant, unattended and sub-threshold stimuli. The main issue in

TIPL studies is the amount of training that has to be carried out in order to find a significant learning effect (i.e., a significant performance improvement between pre- and post-test). Typically, a TIPL experimental paradigm is divided into three main stages: pre-test, training and post-test. Pre- and post-test consist of one daily session, but training can last up to twenty or more daily sessions (for example, Watanabe *et al.*, 2001) because thousands of training trials⁴² are required to observe a significant learning effect. In other words, TIPL experiments are time-consuming⁴³, and this is why it is not always feasible to run TIPL experiments.

Recently, a fast form of TIPL (fast-TIPL) has been studied in the context of perceptual memories⁴⁴ (Lin *et al.*, 2010; Swallow & Jiang, 2010, 2011; Dewald, Sinnott, & Dumas, 2011; Leclercq & Seitz, 2011, 2012a, 2012b, 2012c; Leclercq, Le Dantec, & Seitz, 2014; Leclercq, Hoffing, & Seitz, 2014). Fast-TIPL has been shown within a single training trial (Lin *et al.*, 2010), and this greatly reduced time frame obviously makes it much easier to study the phenomenon.

3.3 FAST TASK-IRRELEVANT PERCEPTUAL LEARNING: THE FIRST EVIDENCE

Starting from the evidence that the human memory system is not able to encode and subsequently retrieve all the information presented in the environment (Miller, 1956), a huge number of studies have been devoted to exploring those factors that might increase the memorability of this information. For example, when a briefly presented scene is *distinctive*, participants encode it better and successfully recognize it later. Both low-level features (such

⁴² There have been TIPL experiments in which the training was shorter than that of the two most influential TIPL studies (Watanabe *et al.*, 2001; Seitz & Watanabe, 2003). However, these studies, too, were time-consuming: for example, in Seitz and colleagues (2005) participants performed 6000 training trials; in Nishina and colleagues (2007) participants performed 5600 training trials; in Seitz and colleagues (2009) participants performed 7000 training trials. This shows that for TIPL to occur, extensive training is mandatory.

⁴³ It takes at least one week to complete a TIPL experiment, and because of the extensive training required it is not always easy to find participants. Moreover, when the participants are paid to take part, TIPL experiments are obviously very expensive to run.

⁴⁴ Unlike fast-TIPL, TIPL has been extensively studied in the context of low-level perceptual learning (for example, TIPL has been demonstrated for motion: Watanabe *et al.*, 2001; for orientation: Nishina *et al.*, 2007; and for contour integration: Rosenthal & Humphreys, 2010).

as low vs high contrast) and high-level ones (such as semantic information) can increase the distinctiveness of a scene (Hunt & Worthen, 2006), which in turn momentarily increases attention, allowing a better memorization of the scene: attention therefore plays a fundamental role in memory formation (Awh & Jonides, 2001; Wolfe, Horowitz, & Michod, 2007).

In 2010, Lin and colleagues investigated whether information to which attention is not primarily directed, but which is present when a behavioural event occurs, is better encoded into memory. The authors experimentally tested whether the process of image encoding can be triggered not only by the content of the image, but also by the time in which the image is presented, in a condition of reduced attention (a dual-task). This is a comparable experimental question to that of Seitz and Watanabe (2003) in the context of low-level task-irrelevant perceptual learning (TIPL). Lin and colleagues (2010) presented participants with a dual-task paradigm: participants were required to perform a primary task consisted of a rapid serial visual presentation (RSVP) task in the fovea (a target identification task, in which participants were required to identify a target presented among distractors)⁴⁵, while they were required also to memorize images⁴⁶ rapidly presented in the peripheral visual field in association with the primary task stimuli (target and distractors). A trial consisted of a sequence of sixteen images (image sequence), each one paired with a primary task stimulus. After the image sequence was presented, participants were required first to report the identity of the primary task target (i.e., type the letter key corresponding to the identity of the white letter), and then to perform a recognition task (the secondary task). In the secondary task, a single test image was presented and participants had to make an old/new decision about the image (i.e., report whether they recognized the image from the previous image sequence or not) (Figure 3.1).

⁴⁵ At the end of each trial, participants were instructed to report the identity of the white letter (target) which was presented among black letters (distractors).

⁴⁶ The images were full-field photographs of urban and natural scenes, taken from the LabelMe Natural and Urban Scenes database (Oliva & Torralba, 2001).



Figure 3.1 - Schematic of an experimental trial used in Lin and colleagues (2010). The figure represents a typical display sequence of the experiment: participants were presented with both a stream of letters at fixation, and a stream of images in the background. Then, they were required first to report the identity of the target (the white letter), second to make an old/new decision about a test image (image taken from reference: Lin *et al.*, 2010).

The results showed that participants properly focused their attention on the primary task (i.e., the average performance accuracy in the RSVP task was near 100%), but the most important and surprising result concerned the secondary task. Here, participants' performance (i.e., their recognition accuracy) was better for test images previously paired with the primary task targets, than for test images previously paired with the primary task distractors, despite the fact that, in a subsequent debriefing stage, participants reported having had the impression of not remembering any image. Moreover, the authors replicated the aforementioned pattern of results using a sensory cross-modal experimental paradigm, in which the primary task consisted of a tone detection task (i.e., auditory modality), while the secondary task was exactly the same as in the previous experiment (i.e., visual modality). This result strengthened the idea that the encoding process can be triggered by behaviourally relevant points in time (i.e., target presentation), and it proved that this mechanism occurs regardless of sensory modality (Lin *et al.*, 2010).

Overall, the study by Lin and colleagues (2010) provided evidence of a learning mechanism similar to TIPL. In both TIPL and fast-TIPL, task-irrelevant stimuli are learned better when presented at behaviourally relevant points in time: the association between the occurrence of a task-irrelevant stimulus and the occurrence of a primary task target represents the

fundamental key point to give rise to the learning of the task-irrelevant stimuli in both learning mechanisms. However, two important points need to be made. First, there is a crucial difference between TIPL experimental paradigms and the experimental paradigm proposed by Lin and colleagues (2010) as regards the properties of the task-irrelevant stimuli. For TIPL to occur, task-irrelevant stimuli must not be presented at a supra-threshold level (Tsushima *et al.*, 2008), while the task-irrelevant stimuli (the images) in the study by Lin and colleagues (2010) are supra-threshold. The second point regards the use of the expression *task-irrelevant stimuli* for the secondary task stimuli. In TIPL experimental paradigms, the stimuli presented in the peripheral visual field during training are completely task-irrelevant, because participants are not required to perform a task on these stimuli while solving the primary task; in the experimental paradigm by Lin and colleagues (2010), the stimuli presented in the peripheral visual field are important, because participants are required to memorize them while solving the primary task. However, since the stimuli presented in the peripheral visual field in both TIPL studies and in the study by Lin and colleagues (2010) cannot be used to solve the primary task, given the absence of any link between those stimuli and the primary task stimuli, some authors have used the expression *task-irrelevant stimuli* in both contexts (Leclercq & Seitz, 2011, 2012a, 2012b, 2012c).

To conclude, it is important to bear in mind that the study by Lin and colleagues (2010) was the first to demonstrate that a sort of TIPL can occur in the time scale of a single trial: in other words, it was the first to provide evidence of the phenomenon of fast task-irrelevant perceptual learning (fast-TIPL)⁴⁷.

3.4 THE CONSTRAINTS OF FAST TASK-IRRELEVANT PERCEPTUAL LEARNING

After the aforementioned work (Lin *et al.*, 2010) which first demonstrated the phenomenon of fast task-irrelevant perceptual learning (fast-TIPL), further studies were conducted in order to define the constraints under which fast-TIPL can be observed.

⁴⁷ Lin and colleagues (2010) did not coin the expression *fast task-irrelevant perceptual learning*: it was first used later by Leclercq and Seitz (2011).

3.4.1 Presence of distractors in the primary task

One of the constraints for fast-TIPL to occur is that both targets and distractors must be presented in the primary task (Leclercq & Seitz, 2011).

In 2011, Leclercq and Seitz investigated the key task conditions necessary to observe fast-TIPL. In a first experiment (Experiment 1), the experimental paradigm was similar to that used by Lin and colleagues (2010), except that the primary task was a simple target detection task. In this primary task, participants were presented only with targets (white squares) without distractors, and they had to rapidly press a button when the targets appeared (Figure 3.2, panel A). The results showed no fast-TIPL (i.e., no advantage in the recognition of images paired with primary task targets). However, in a subsequent experiment (Experiment 2), when in the primary task the targets were presented among distractors (Figure 3.2, panel B), an advantage was observed in the recognition of images paired with primary task targets compared to images paired with primary task distractors, indicating that fast-TIPL had occurred. The same pattern of results was obtained using different stimuli and tasks (i.e., in Experiment 3, a letter identification task⁴⁸ -the primary task- was used in which only targets were presented, while in Experiment 4, both targets and distractors were presented). To explain these results, the authors argued that when the target is presented alone (as in Experiments 1 and 3), the onset of the target is sudden and it exogenously orients attention at the target location (central visual field), making no attentional resources available for the process of image encoding (i.e., attentional capture hypothesis⁴⁹) (Leclercq & Seitz, 2011).

⁴⁸ The difference between the target detection task used in Experiments 1 and 2 and the target identification task used in Experiments 3 and 4 lies not only in the stimuli employed (squares vs letters), but also in the tasks *per se*; in Experiments 1 and 2, participants just had to detect a target and therefore give an immediate response, while in Experiments 3 and 4 participants had to report the identity of the target at the end of the trial, and therefore give a delayed response (Leclercq & Seitz, 2011).

⁴⁹ The attentional capture hypothesis is supported by several previous experiments, which have shown an enhancement in target detection when the target has a sudden onset, and not for example when the target onset consists in a change in colour (Yantis & Jonides, 1984; Jonides & Yantis, 1988)

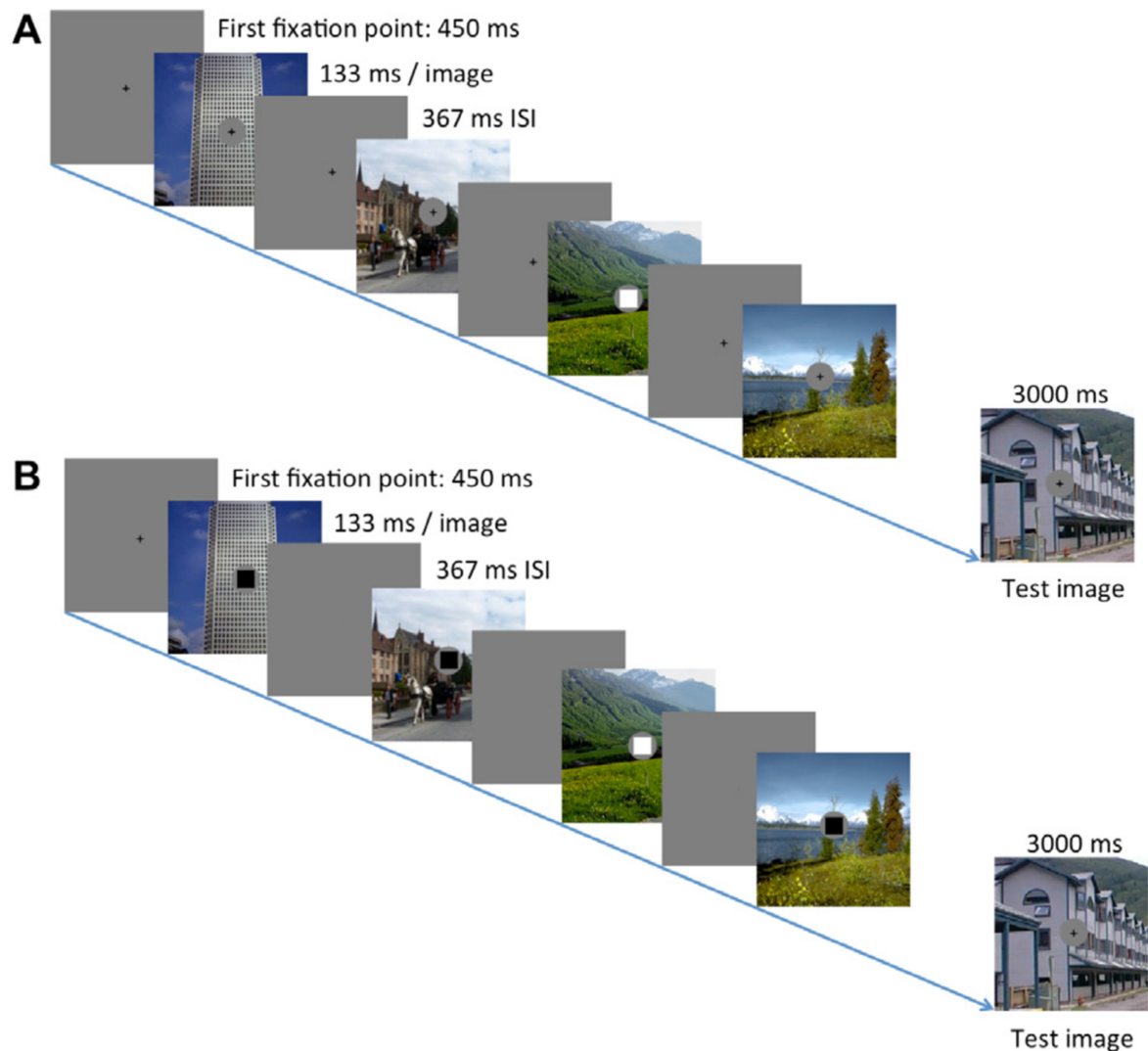


Figure 3.2 - Schematic of an experimental trial used in Leclercq and Seitz (2011). Participants had to perform a target detection task, and subsequently an image recognition task. Panel A: example of an experimental trial used in the Experiment 1, in which only the target (white square) was presented in the RSVP stream. Panel B: example of an experimental trial used in the Experiment 2, in which the target was presented among distractors (black squares) in the RSVP stream (image taken from reference: Leclercq & Seitz, 2011).

3.4.2 Attention towards the secondary task stimuli

Another constraint for fast-TIPL to occur is that participants have to pay attention to the secondary task stimuli (Swallow & Jiang, 2011; Leclercq & Seitz, 2012c).

One of the main differences between TIPL and fast-TIPL experimental paradigms can be found in the properties of the task-irrelevant stimuli: for TIPL to occur, the task-irrelevant stimuli have to be sub-threshold, while in fast-TIPL, the task-irrelevant stimuli are presented at a

supra-threshold level. The need for sub-threshold task-irrelevant stimuli in TIPL is justified by the fact that attention impacts negatively on TIPL: if a task-irrelevant stimulus is presented at a supra-threshold level, the attentional system detects and suppresses the stimulus, inhibiting its learning (Tsushima *et al.*, 2008; Roelfsema *et al.*, 2010). In fast-TIPL, on the other hand, attention is necessary, and it enhances the encoding process of the secondary task stimuli (Leclercq & Seitz, 2012c).

In 2011, Dewald and colleagues, presented participants with a primary task consisting of a rapid serial visual presentation (RSVP) task (a repetition detection task). In each trial of the primary task, a sequence of images was presented: participants were required to rapidly respond to the immediate repetition of an image (the primary task stimulus), while they were exposed to a written word (task-irrelevant stimulus) superimposed on each image. At the end of the primary task, a surprise recognition task (the secondary task) was given to participants on the previously presented words. Here then, unlike in previous studies (such as Lin *et al.*, 2010), participants were not required to memorize the task-irrelevant stimuli (written words) paired with the primary task stimuli (images) when performing the primary task. In other words, attention towards the task-irrelevant stimuli was not necessary. The results showed no fast-TIPL; instead, task-irrelevant stimuli paired with the primary task targets were recognized at levels significantly below chance. This result seems to indicate that the attentional system inhibited the encoding process of task-irrelevant stimuli (Dewald *et al.*, 2011).

A study by Swallow and Jiang (2011) took a closer look at the role of attention in fast-TIPL. Their experimental paradigm was similar to that of Lin and colleagues (2010), but they divided participants into two groups: one group was told to pay attention to the images presented in the peripheral visual field because of the subsequent image recognition task (attention group), while the other group was told to ignore the images (no-attention group). The results showed fast-TIPL only in the attention group and not in the no-attention group, suggesting that attention towards the secondary task stimuli is needed in order to observe fast-TIPL (Swallow & Jiang, 2011).

At first glance, the results obtained in Dewald and colleagues (2011) and in Swallow and Jiang (2011) might seem to conflict with each other: in the first study, attention inhibited the encoding process of task-irrelevant stimuli, while in the second, attention towards task-

irrelevant stimuli was necessary to observe fast-TIPL. However, if we bear in mind exactly what is meant by the expression *task-irrelevant stimuli* in the context of fast-TIPL, it becomes clear that these results are only apparently contradictory. As previously reported (see section 3.3), the use of the expression *task-irrelevant stimuli* in fast-TIPL signifies merely that the secondary task stimuli presented in temporal association with the primary task stimuli cannot help the participant to solve the primary task: those stimuli are therefore task-irrelevant with respect to the primary task. In the study by Dewald and colleagues (2011), as in TIPL studies, the secondary task stimuli were also task-irrelevant with respect to the participants, because participants were not told about the subsequent recognition task, while in Swallow and Jiang (2011) the secondary task stimuli were task-irrelevant with respect to the primary task, but not with respect to the participants (the attention group). It is this difference that explains why the role of attention is so different in the two studies described above: when the secondary task stimuli are task-irrelevant with respect to the participants, those stimuli are distracting and attention inhibits them in order to better perform the primary task (Dewald *et al.*, 2011), while when the secondary task stimuli are task-relevant with respect to the participants, attention enhances the encoding process of those stimuli (Swallow & Jiang, 2011).

In 2012, Leclercq and Seitz systematically explored the role of attention in fast-TIPL by eliciting attentional orienting toward a designated location of the visual field. The authors used an exogenous attention experimental paradigm (for a similar paradigm used in the context of a TIPL experiment, see Choi *et al.*, 2009) combined with a fast-TIPL paradigm (similar to Lin *et al.*, 2010). In a first experiment, participants were asked to perform a target identification task (the primary task) in the fovea, while images were presented in the peripheral visual field, and participants were required to memorize them. Attention was manipulated using arrows as targets of the primary task. The hypothesis was that if attention had a negative impact on fast-TIPL (as in Dewald *et al.*, 2011, and in TIPL studies), images paired with primary task targets would be recognized worse than images paired with primary task distractors in a subsequent recognition task, because the primary task targets (the arrows) automatically direct attention towards the images (Tipples, 2002). Contrary to this hypothesis, the results showed fast-TIPL for images paired with primary task targets, indicating that attention has a positive impact on fast-TIPL, as found in the study by Swallow and Jiang (2011). Another interesting result refers

to the recognition rates of images paired with primary task distractors: when the authors compared the recognition rates for images presented before (pre-target images) and after (post-target images) the primary task targets, they found that the post-target images were recognized better than the pre-target ones, with a recognition rate comparable to that found for images paired with primary task targets. To explain this finding, the authors suggested that the exogenous orienting target might help to endogenously direct attention towards the images also after its presentation, because in each trial, once the exogenous orienting target had been presented, participants only had to pay attention to the images. The results of this experiment therefore supported the hypothesis that attention is beneficial in fast-TIPL. However, to get a better understanding of the role of attention in fast-TIPL, the authors conducted another experiment. The experimental paradigm was the same as in the previous experiment, except that during the target identification task (the primary task), two images (one to the left and another to the right with respect to the location of the primary task) were paired simultaneously with the occurrence of each primary task stimulus. This experimental paradigm is more similar to the experimental TIPL paradigm used by Choi and colleagues (2009), who had previously found that attention has a negative impact on TIPL. The authors' hypothesis was in line with that of Choi and colleagues (2009): if attention has a positive impact on fast-TIPL, higher recognition rates are to be expected for images presented in the location where the arrowheads point. The results showed no difference in recognition rates between images presented at the location where the arrowheads pointed or at the opposite location, even though fast-TIPL was found (i.e., higher recognition rates for images paired with primary task targets than for images paired with primary task distractors). This result suggests that fast-TIPL occurs regardless of the direction to which attention is directed (Leclercq & Seiz, 2012c).

Overall, these findings raise the question of why attention has an opposite effect on the learning of task-irrelevant stimuli in TIPL and fast-TIPL (i.e., a negative impact in TIPL and a positive one in fast-TIPL). Once again, the key to answering this question lies in the use of the expression *task-irrelevant stimuli*. In TIPL experimental paradigms, the stimuli paired with the primary task stimuli are task-irrelevant both with respect to participants and with respect to the primary task. In fast-TIPL experimental paradigms, on the other hand, because participants have to perform a dual-task, the secondary task stimuli are task-irrelevant only with respect

to the primary task (and task-relevant with respect to participants). This explains why the role of attention is completely different in TIPL and fast-TIPL: in TIPL, the task-irrelevant stimuli are distracting for participants, and thus the attentional system inhibits their processing (Tsushima *et al.*, 2008), whereas in fast-TIPL, the task-irrelevant stimuli are of importance for a subsequent task, and the attentional system therefore enhances their processing (Swallow & Jiang, 2011; Leclercq & Seitz, 2012c).

3.4.3 Explicit secondary task

This constraint follows the previous one: in order to observe fast-TIPL, the secondary task has to be explicit (Leclercq & Seitz, 2012b).

In 2012, Leclercq and Seitz investigated whether attention towards the secondary task stimuli is sufficient to observe fast-TIPL, or whether a higher processing level of those stimuli is required. The authors designed three experiments in which they systematically increased the processing level of the secondary task stimuli in a fast-TIPL experimental paradigm. They required participants respectively to ignore (Experiment 1), pay attention to (Experiment 2)⁵⁰, and memorize (Experiment 3) the secondary task stimuli. The results of Experiment 1 and Experiment 3 were in line with previous studies: no fast-TIPL was found in Experiment 1, while it was found in Experiment 3. An interesting finding emerged in Experiment 2: when attention was directed towards the images, but explicit memorization of the images was not required, fast-TIPL occurred in the male participants, but not in the female ones. Although the reasons for this gender effect are still unclear⁵¹, this finding indicates that attention to the secondary task stimuli is necessary but not sufficient to produce fast-TIPL, and that explicit memorization

⁵⁰ The authors manipulated participants' attention to the images (the secondary task stimuli), by asking participants performing the primary task to perform a repetition image task at the same time (i.e., detect a possible repetition in the image sequence) (Leclercq & Seitz, 2012b).

⁵¹ The performances of male and female participants in the repetition image task was analysed separately but no difference was found in accuracy. Thus, the absence of fast-TIPL in female participants is not attributable to a difference in the overall performance between male and female participants. To account for the gender effect, the authors put forward various hypotheses related to gender differences either in the release of neuromodulators (such as higher levels of dopamine release in males; for example, Urban *et al.*, 2010), or in spatial abilities (such as local bias in female; for example, Kimchi, Amishav, & Sulitzeanu-Kenan, 2009) (Leclercq & Seitz, 2012b).

of the secondary task stimuli is required in order to observe fast-TIPL in both male and female participants (Leclercq & Seitz, 2012b).

3.4.4 No immediate arbitrary stimulus-response mapping

In 2010, Swallow and Jiang reported that fast-TIPL can be disrupted when an arbitrary stimulus-response mapping is used in the primary task (Swallow & Jiang, 2010).

The authors used a fast-TIPL experimental paradigm similar to that of Lin and colleagues (2010). In one experiment (Experiment 1), a simple detection task was used as the primary task: participants had to rapidly press a button when they saw a target consisting of a red or a green square, and inhibit the response when they saw a distractor consisting of a black square. In a second experiment (Experiment 2), the same primary task was used, except that two different responses were associated with the occurrence of the targets: participants had to press a button (the “R” key on the keyboard) when they saw a red square, and another button (the “G” key) when they saw a green square (and to inhibit the response when they saw a distractor consisting of a black square). In Experiment 2, then, the stimulus-response mapping was completely arbitrary. The results showed fast-TIPL in Experiment 1, but not in Experiment 2. In order to explain these results, Swallow and Jiang (2010) claimed that the use of arbitrary stimulus-response mapping determines a depletion of attentional resources, which in turn prevents the encoding of images paired with the primary task targets (meaning that when a primary task target is presented on the screen, participants have to access the stimulus-response mapping given and select an arbitrary response: this process requires a huge amount of attentional resources which are therefore not available to encode the task-irrelevant stimulus paired with the target occurrence) (Swallow & Jiang, 2010).

It should be pointed out that the crucial factor in fast-TIPL is not the type of stimulus-response mapping *per se*, but the interplay between the type of stimulus-response mapping and when the response is required: for example, when an arbitrary stimulus-response mapping is given to participants, but the response is required at the end of each experimental trial (delayed response), fast-TIPL is observed (Lin *et al.*, 2010).

3.5 WHAT IS LEARNED THROUGH FAST TASK-IRRELEVANT PERCEPTUAL LEARNING?

In fast task-irrelevant perceptual learning (fast-TIPL), better recognition occurs of those task-irrelevant stimuli temporally paired with the occurrence of primary task targets (Lin *et al.*, 2010). *Better recognition* is a general expression, and does not specify what type of information is learned through fast-TIPL, or in other words, the depth of the stimulus encoding. A better recognition of a task-irrelevant stimulus could be accounted for by the learning of salient features of the stimulus (perceptual learning account), by the familiarity of the stimulus (familiarity account), or by the episodic information contained in the stimulus (episodic account).

Leclercq and colleagues published a study in 2014 which systematically investigated what type of information is learned through fast-TIPL by using a modified version of the fast-TIPL experimental paradigm adopted by Lin and colleagues (2010). During the image recognition task (the secondary task), participants were not only required to make an old/new decision about each image, but were also required to rate the confidence of their judgments, by using a rating memory scale with six levels, which also assessed the familiar/remember properties of old classified images⁵². Participants were also tested for episodic information contained in the images. During the primary task, two images were simultaneously paired with the occurrence of each primary task stimulus: one image was presented on the right, and the other on the left of the centre of the screen. During the image recognition task, participants were also asked to report the screen location (right or left; i.e., this is an episodic information) of the images that they had classified as old. The hypothesis was that, if fast-TIPL occurred and if participants correctly reported the screen location of images paired with the primary task targets, this would account for an episodic encoding of the images. The results showed significantly better recognition for images paired with primary task targets than for images paired with primary task distractors (i.e., fast-TIPL), with a higher number of remember ratings for images paired with primary task targets; moreover, participants properly assigned the highest confidence remember ratings to images paired with primary task targets, and for

⁵² The authors adopted the rating memory scale developed by Ingram, Mickes, & Wixted, (2012), in which confidence ratings from 1 (i.e., highest confidence) to 3 indicate a “new” item, and confidence ratings from 4 to 6 (i.e., highest confidence) indicate a “old” item. When participants classified an item as “old”, they were also required to make a remember/familiar judgement (Ingram *et al.*, 2012).

those images they also correctly reported the image screen location. After having observed these results, the authors claimed that, in fast-TIPL, an enhancement occurs in the encoding of episodic information paired with primary task targets.

To conclude, it seems that during fast-TIPL, episodic information is learned which is intrinsic to the task-irrelevant stimuli paired with primary task targets.

3.6 THE ATTENTIONAL BOOST EFFECT

As outlined above, the expression *fast task-irrelevant perceptual learning* (fast-TIPL) refers to the phenomenon of enhanced memorization of task-irrelevant information presented at behaviourally relevant points in time, and this phenomenon has been demonstrated using different primary tasks, and across different sensory modalities. Moreover, attention plays a fundamental role in fast-TIPL, enhancing the encoding process of task-irrelevant information (Lin *et al.*, 2010; Swallow & Jiang, 2011; Leclercq & Seitz, 2012c). In order to explain how attention promotes fast-TIPL, in 2010, Swallow and Jiang theorized the attentional boost effect (ABE) (Swallow & Jiang, 2010). The ABE is a counter-intuitive effect: in a condition of divided attention, as a dual-task typically used in a fast-TIPL paradigm, one might expect that increasing attention to the task-relevant stimuli of the primary task would determine a decrease in the processing of temporally paired task-irrelevant information (named dual-task interference), because attention is limited in capacity (Kinchla, 1992). However, the experimental demonstration of the counter-intuitive ABE (Lin *et al.*, 2010; Swallow & Jiang, 2010) challenged this idea. Swallow and Jiang (2010) theorized that, in a fast-TIPL paradigm, the occurrence of a primary task target causes an increase in attention (named attentional boost) at the specific moment in time in which the primary task target appears: moreover, attention does not remain focused on the primary task, but spreads towards the information temporally paired with the primary task targets. In other words, in a dual-task paradigm, the detection of a primary task target boosts attention, which in turn promotes the processing

and encoding into memory of the task-irrelevant stimulus temporally paired⁵³ with the primary task target: this is the ABE (Swallow & Jiang, 2010, 2011, 2012, 2013, 2014).

It must be stressed that in the ABE, the increase in attention is temporally specific (because it occurs when a primary task target is presented), but spatially independent (because attention does not remain focused on the primary task, but spreads to the background) and modality independent (because the primary and the secondary tasks can involve same or different sensory modalities) (Swallow & Jiang, 2010, 2011, 2012, 2013, 2014). Moreover, the ABE has been demonstrated using different types of stimuli (for example, using verbal stimuli instead of images as secondary task stimuli, see Mulligan, Spataro, & Picklesimer, 2014).

A short introductory note is necessary in order to explain another issue surrounding the ABE. In fast-TIPL experimental paradigms, the primary task usually consists of a target detection or identification task, which means that in each trial of the primary task, participants have to respond to a target, and inhibit the response when a distractor is presented. In this scenario, it is possible to hypothesize that fast-TIPL reflects either an enhancement process due to target selection (the enhancement hypothesis, see Driver, 2001), or an inhibition process due to distractors rejection (the inhibition hypothesis, see Moher & Egeth, 2012). In 2014, Swallow and Jiang provided the experimental evidence that, as they had previously theorized, the enhancement hypothesis accounts for the ABE. In other words, they proved that the ABE consists of an enhancement in the encoding process triggered by primary task target detection, ruling out the possibility that an inhibition triggered by distractors rejection plays a role in the ABE (Swallow & Jiang, 2014).

3.7 COMPARING TASK-IRRELEVANT PERCEPTUAL LEARNING (TIPL) AND FAST-TIPL

At first glance, task-irrelevant perceptual learning (TIPL) and fast-TIPL might appear to be two very similar learning mechanisms, because in both, learning occurs for task-irrelevant stimuli presented at behaviourally relevant points in time (Seitz and Watanabe, 2003; Lin *et al.*, 2010).

⁵³ The ABE occurs in a condition of temporal pairing between a primary task target and a task-irrelevant stimulus. However, for fast-TIPL to occur, only the aforementioned temporal overlap is necessary, while an onset synchrony between the primary task target and the task-irrelevant stimulus is not mandatory.

There are important differences between them, however. The first regards the role played by attention: in TIPL, attention inhibits the learning of task-irrelevant stimuli (Choi *et al.*, 2009), while in fast-TIPL, it gates learning (Swallow & Jiang, 2011; Leclercq & Seitz, 2012c). A second difference is connected to the first: for TIPL to occur, because of the inhibitory role of attention, task-irrelevant stimuli have to be presented at a sub-threshold level, while in fast-TIPL this is not the case. Moreover, TIPL and fast-TIPL have two different time courses: while in TIPL, thousands of training trials are required to give rise to the learning of task-irrelevant stimuli⁵⁴ (Watanabe *et al.*, 2001), fast-TIPL can occur within a single trial (Lin *et al.*, 2010). However, it is still impossible to say whether the aforementioned differences between TIPL and fast-TIPL arise from an intrinsic difference in these two learning mechanisms, because to date, TIPL and fast-TIPL have been studied using different methodologies and different stimuli⁵⁵. There are two possibilities here: on the one hand, TIPL and fast-TIPL might share the same underlying mechanisms, but the use of different stimuli brings about differences in the observed effects produced by these two learning mechanisms; on the other hand, the underlying mechanisms of TIPL and fast-TIPL might be completely different and the similarities between the two showed in several findings might be merely superficial.

In conclusion, further studies are still needed at this stage for a clearer understanding of the similarities and the differences between TIPL and fast-TIPL.

⁵⁴ Because of the extensive training required to observe TIPL, some authors have referred to this phenomenon using the expression *slow-TIPL*.

⁵⁵ In TIPL, learning is commonly showed for low-level task-irrelevant features/stimuli, while in fast-TIPL visual memory for task-irrelevant stimuli is tested. Perceptual learning of low-level features/stimuli and visual memory are two distinct brain processes with different time courses.

CHAPTER 4

Fast task-irrelevant perceptual learning study

4.1 CHAPTER OVERVIEW

This chapter presents an experiment designed to explore how the modulation of the primary task difficulty affects the phenomenon of fast task-irrelevant perceptual learning (fast-TIPL). A brief introduction regarding the topic under investigation in the experiment is provided at the beginning, including a short description of the perceptual phenomenon of crowding. The experiment is then described in detail: the aim, the method, and the results are illustrated. A brief discussion is provided at the end.

4.2 INTRODUCTION

Chapter 3 gave a description of the phenomenon of fast task-irrelevant perceptual learning (fast-TIPL). To recapitulate briefly, in fast-TIPL, information to which attention is not primarily directed, but which is presented simultaneously with a behavioural event⁵⁶ is better encoded into memory than information presented at other points in time (Lin *et al.*, 2010).

Fast-TIPL therefore resembles task-irrelevant perceptual learning (TIPL): in both those learning mechanisms, perceptual learning occurs for task-irrelevant stimuli. It must be stressed that the expression *task-irrelevant stimuli* in both TIPL and fast-TIPL contexts means any kind of stimuli which are task-irrelevant with respect to the task in which participants are primarily engaged. In other words, in fast-TIPL the use of the expression *task-irrelevant stimuli* refers to the fact that, in a dual-task condition, the secondary task stimuli are unrelated to the

⁵⁶ Typically, in an artificial laboratory context, a behavioural event corresponds to a target stimulus presentation.

primary task stimuli, and cannot be used to solve the primary task⁵⁷ (Lin *et al.*, 2010).

In order to study the role of task-irrelevant information in visual perceptual learning, the use of a fast-TIPL experimental paradigm instead of a TIPL one offers a significant advantage in terms of the time spent performing the experiment. While TIPL experiments are time-consuming, requiring extensive training in order to observe a significant learning effect (meaning that training can last up to twenty or more daily sessions; Watanabe *et al.*, 2001), fast-TIPL can be found even in the time scale of a single training trial (Lin *et al.*, 2010).

After the fast-TIPL was first demonstrated (Lin *et al.*, 2010), further studies were conducted in order to define the constraints under which fast-TIPL can be observed. Those constraints are: the presence of both targets and distractors in the primary task (Leclercq & Seitz, 2011), attention towards the secondary task stimuli (Swallow & Jiang, 2011; Leclercq & Seitz, 2012c), an explicit secondary task (Leclercq & Seitz, 2012b), and no immediate arbitrary stimulus-response mapping in the primary task (Swallow & Jiang, 2010; Lin *et al.*, 2010).

Perhaps the most intriguing constraint is the one that postulates that attention towards the secondary task stimuli is needed for fast-TIPL to occur, because it suggests a different role of attention in TIPL and fast-TIPL. While attention impacts negatively on TIPL by inhibiting the learning of task-irrelevant stimuli (Choi *et al.*, 2009), in fast-TIPL, it gates learning of those stimuli (Swallow & Jiang, 2011; Leclercq & Seitz, 2012c). In TIPL, the task-irrelevant stimuli presented in the course of training are distracting for participants, because participants do not have to perform a task involving those stimuli: as a consequence, the attentional system inhibits the processing of the task-irrelevant stimuli when they are presented at a supra-threshold level (Tsushima *et al.*, 2008). In fast-TIPL, on the other hand, task-irrelevant stimuli are of importance for a subsequent task (and the participants are told this explicitly before the experiment starts; Leclercq & Seitz, 2012b). It is this crucial distinction that accounts for the differing role of attention in the two learning mechanisms.

In fast-TIPL, attention is therefore needed to process task-irrelevant stimuli and it enhances the encoding process of those stimuli (Swallow & Jiang, 2011; Leclercq & Seitz, 2012c). In order

⁵⁷ In TIPL, on the other hand, the task-irrelevant stimuli are task-irrelevant with respect both to the primary task and to the participants (i.e., participants are not required to perform a task on those stimuli, which are also unattended and presented at a sub-threshold level; for example, Watanabe *et al.*, 2001).

to account for this evidence, Swallow and Jiang theorized the attentional boost effect (ABE): in a dual-task condition (i.e., a condition of divided attention), the occurrence of a primary task target causes an increase in attention (named attentional boost) which is temporally specific, but spatially and modality independent. In other words, the presentation of a primary task target determines an attentional boost, which in turn promotes the processing and the learning of task-irrelevant information temporally paired with the primary task target occurrence (Swallow & Jiang, 2010, 2011, 2012, 2013, 2014).

Taking into account that attention is limited in capacity (Kinchla, 1992), the finding of ABE appears counter-intuitive and conflicts with the dual-task interference literature, which postulates that in a dual-task condition the increase in attention to one task determines a decrease in attention to a second task. To be more precise, the dual-task interference literature predicts that, in a typical fast-TIPL paradigm, a dual-task interference occurs: increasing attention to the primary task target determines a decrease in the processing of temporally paired task-irrelevant information (for example, Kinchla, 1992; Pashler, 1994)⁵⁸.

The ABE would also seem to be in conflict with the load theory of attentional selection (Lavie & Tsai, 1994; Lavie, 1995; Lavie, Hirst, de Fockert, & Viding, 2004), which is based on the assumption that attention, as well as perceptual and cognitive processes, is limited in capacity. Again, in the load theory of attentional selection, the prediction is that increasing attention to a task-relevant stimulus impairs the processing of paired task-irrelevant information. However, contrary to other theories, the load theory of attentional selection accounts for the possibility of the processing and learning of task-irrelevant information: when the processing of task-relevant stimuli required a low perceptual and cognitive load, then the remaining available resources are directed to the processing of task-irrelevant stimuli⁵⁹, enabling the learning of those stimuli (Lavie & Tsai, 1994; Lavie, 2005).

The ABE and the dual-task interference are therefore not mutually-exclusive: which one

⁵⁸ The same hypothesis was stated in *early selection* theories, which postulate that attention can be considered as a *perceptual filter*, restricting the perceptual processing to attended information only (for example, Broadbent, 1958) and in *late selection* theories, which postulate that the perceptual processing occurs for all the information presented in the environment, and attention determines which information reaches awareness (for example, Deutsch & Deutsch, 1963; Duncan, 1980).

⁵⁹ The load theory of attentional selection is based on the assumption that the human brain uses all the available cognitive resources.

prevails, depends on the attentional and cognitive load needed to process the task-relevant stimuli (Lavie, 2005; Swallow & Jiang, 2013).

The present study attempts to deepen the understanding of whether and how the modulation of the primary task difficulty (i.e., the modulation of the attentional and cognitive load required to perform the primary task) affects subsequent recognition of task-irrelevant stimuli associated with the presentation of the primary task targets and distractors in a standard fast-TIPL paradigm (similar to Lin *et al.*, 2010). In a 2-day experiment, participants performed a primary task consisting of a letter matching task, and a secondary task consisting of an image recognition task. In each trial of the primary task, participants first had to detect a target among distractors, and secondly identify whether two target letters were the same or different. The two target letters were not presented alone, but embedded in two 3-letter clusters: the primary task difficulty was therefore modulated by varying the distance between the target and the side letters (while keeping the eccentricity of the target letters constant). This procedure made it possible to obtain both an easy and a difficult (crowded⁶⁰) condition. Moreover, while performing the primary task, participants were also required to pay attention to and memorize task-irrelevant stimuli presented in the background, because those stimuli were successively tested in the secondary task.

4.2.1 Crowding

In 1923, Korte described the phenomenon of crowding for the first time: *“it is as if there is a pressure on both sides of the word that tends to compress it. Then the stronger, i.e. the more salient or dominant letters, are preserved and they ‘squash’ the weaker, i.e. the less salient letters, between them”*⁶¹ (Korte, 1923).

In more general terms, in the domain of visual perception, the term *crowding* refers to the behavioural phenomenon of impaired identification of a target stimulus (for example, a letter or an object) when it is surrounded by flankers. In other words, a target that can be clearly identified when presented in isolation is no longer identifiable when presented in cluster: the

⁶⁰ See the following subsection (4.2.1) for a brief description of the phenomenon of crowding.

⁶¹ Korte, W. (1923). Über die Gestaltauffassung im indirekten Sehen. *Zeitschrift für Psychologie*, 93, 17-82. Quoted translation by Uta Wolfe appearing in Pelli *et al.*, 2004.

target appears impossible to distinguish from flankers. This evidence makes crowding a fundamental limit of the conscious identification of targets (Levi, 2008). To give a real-life example, crowding impairs letter identification in the peripheral visual field, thereby compromising the reading process, and making this phenomenon clinically relevant for the dyslexic population⁶² (Martelli *et al.*, 2009).

An important characteristic of crowding and the most relevant in the experiment here described, is that crowding depends on both the eccentricity of a target and how closely spaced the flankers are. At a given eccentricity, identification of a target improves as the distance between the target and the flankers increases⁶³ (Bouma, 1970). It is therefore possible to experimentally modulate the difficulty of a task (for example, a letter identification task) by varying the distance between the target and the flankers.

To conclude, it should be pointed out that crowding is a ubiquitous phenomenon that occurs throughout most of the visual field which has been studied using various stimuli (for example, Gabor patches, letters and faces) and different methodologies (for reviews, Levi, 2008; Whitney & Levi, 2011). Although numerous experiments have been conducted in an attempt to improve the understanding of the phenomenon of crowding, it is still not clear at which stage of the visual process crowding occurs⁶⁴.

4.3 EXPERIMENT

4.3.1 Aim and expected results

The general aim of the experiment was to investigate whether and how the modulation of the primary task difficulty affects the subsequent recognition of task-irrelevant stimuli previously paired with the occurrence of the primary task stimuli (targets and distractors).

⁶² The study by Martelli, Di Filippo, Spinelli, & Zoccolotti (2009) tested the hypothesis that crowding accounts for the reading slowness characteristic of population with developmental dyslexia (Martelli *et al.*, 2009).

⁶³ Bouma (1970) stated that the critical distance between a target stimulus and flankers for crowding to occur depends on the target eccentricity, and not on the target dimensions: the critical distance is proportional to the eccentricity of the target stimulus (Bouma, 1970).

⁶⁴ Recent evidence suggested that crowding occurs at multiple stages of the visual process (Whitney & Levi, 2011).

I expected to find: in the primary task (1) a difference in performance between the two difficulty conditions of the primary task which had been used in the experiment. To be precise, I expected a better performance in the easier condition, which would indicate that I correctly manipulated the *task difficulty* variable; (2) a difference in performance between the two days of the experiment, which would indicate a learning effect; in the secondary task (3) a difference in the recognition performance between images previously paired with the primary task targets and distractors⁶⁵, varying accordingly to the two primary task difficulty conditions.

4.3.2 Methods

(a) Participants

115 naïve students from the University of Trieste (86 females; age range: 18-39) voluntarily participated in the experiment. The sample size exceeds other published studies which have successfully demonstrated significant fast-TIPL effects (for example, Lin *et al.*, 2010).

All participants reported normal or corrected-to-normal visual acuity; however, the visual acuity was not experimentally assessed using standard methods.

Informed consents were obtained before the beginning of the experiment. Procedures were conducted in accordance with the Declaration of Helsinki and approved by the local ethics committee.

(b) Setting

The experiment took place in a dimly illuminated (approx. 50 lux) room. Visual stimuli were presented on a screen (72.5 cm height, 90 cm width) throughout a projector controlled by a MacBook Pro. PsyScopeTM (Cohen, MacWhinney, Flatt, & Provost, 1993) Version X B77 was used for stimuli generation and presentation.

Participants performed the experiment at the same time (group experiment): for this reason, participants sat at different distances from the screen, with an average view distance of 6.5

⁶⁵ A better performance in the secondary task (image recognition task) for images associated with the targets than with the distractors of the primary task, would indicate the occurrence of fast-TIPL.

meters⁶⁶ (view distance range: 3 - 10 meters) (see Supplemental Materials 3, Figure S3.1).

(c) Stimuli and tasks

The backgrounds of all displays were grey (15 cd/m²). 738 full-colour images (72.5 cm height, 90 cm width, i.e. full-screen images) depicting natural scenes from four different categories (open country, mountains, coast and beach, forest) were used. Images were obtained from the LabelMe Natural and Urban Scenes database (Oliva & Torralba, 2001) at 256x256 pixels resolution, up-sampled to 700x700 pixels resolution and then scaled in order to be presented full-screen. A grey stripe (5 cm height, 56 cm width) was superimposed at the centre of each image, containing a central red fixation cross (3 cm height, 3 cm width).

Participants performed first a letter matching task (primary task), while at the same time they were required to memorize stimuli (images) presented in the background. Successively, they performed an image recognition task (secondary task).

LETTER MATCHING TASK (PRIMARY TASK)

An array of upper-case letters (single letter dimension: 3.5 cm height, 3 cm width; font: Helvetica) was superimposed on each image⁶⁷. The array of letters was made up of two 3-letter clusters presented respectively to the left and to the right of the fixation cross. The letters were either white or black: the colour indicated their identity respectively as a target or a distractor stimulus (Figure 4.1). The eccentricity of the central letters of the two 3-letter clusters was maintained constant (18.5 cm from the centre of the fixation cross, corresponding to $\approx 1.63^\circ$ in case of 6.5 meters viewing distance), while the distance between the central and the side letters of each 3-letter cluster (the inter-letter distance, ILD) varied across two conditions. Two different arrangements of the letters embedded in each 3-letter

⁶⁶ The stimuli measures are given in centimetres (as measured on the screen; height x width) and not in degree of visual angle because the view distance was not the same for all participants but it varied across participants. It should be pointed out that the position relative to the screen of each participant varied across participants, but not across days; in other words, on Day 1 and Day 2 of the experiment each participant sat in the same position.

⁶⁷ The array of letters had the same onset and offset times as the image with which it was paired.

cluster were used: in the small-ILD condition the ILD was 4 cm⁶⁸, while in the large-ILD condition the ILD was 7.5 cm (Figure 4.1).

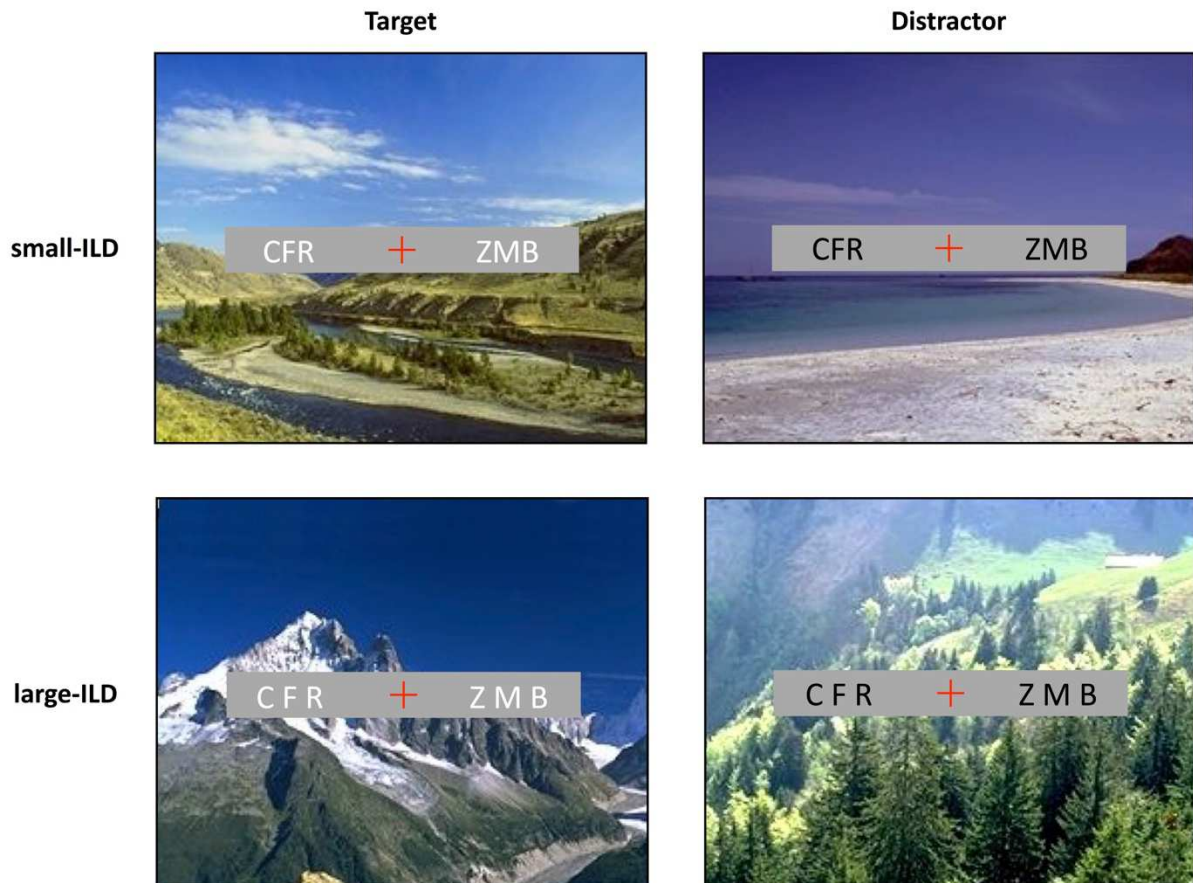


Figure 4.1 - Schematic of the stimuli used in the letter matching task. Target stimuli (arrays of white letters) are represented on the left; distractor stimuli (arrays of black letters) are represented on the right. Arrays of letters with small-ILD and large-ILD were represented respectively at the top and at the bottom of the figure.

The small- and the large-ILD condition represented respectively a *difficult* and an *easy* condition: according to the Bouma's law, the identification of a target critically depends on the distance between the target and the flankers, as the distance increases the identification

⁶⁸ The inter-letter distance (ILD) was calculated as the distance between the central letter and the side letters centroids.

becomes easier (Bouma, 1970).

The central letters of the two 3-letter clusters were always selected from the two consonants F and M, while the side letters were randomly selected from the other consonants of the Italian alphabet, with the only requirement being that no duplicate letters were presented within the same array of letters.

At the beginning of each trial, an auditory stimulus (250 ms) and a screen indicating the trial number (2 s) were simultaneously presented. Then, after a fixation screen (500 ms), seven display stimuli (i.e., images containing the stripe, the fixation cross and the array of six letters) were sequentially presented at 250 ms per image with an inter stimulus interval (ISI) of 500 ms. After the presentation of the last display stimulus, a response screen (*“Same or different letters?”*) appeared for 3 s, and then a next trial began.

In each trial, images in the sequence position 1, 2, 3, 5, 6 and 7 were paired with an array of black letters (distractors), while the image in the sequence position 4 was paired with an array of white letters (target). Participants were instructed first to detect the target (the array of white letters) among distractors and secondly identify whether the central letters of the two 3-letter clusters of the target were the same or different (binary matching task; Figure 4.2). Participants were not told that the target was always presented in the sequence position 4.

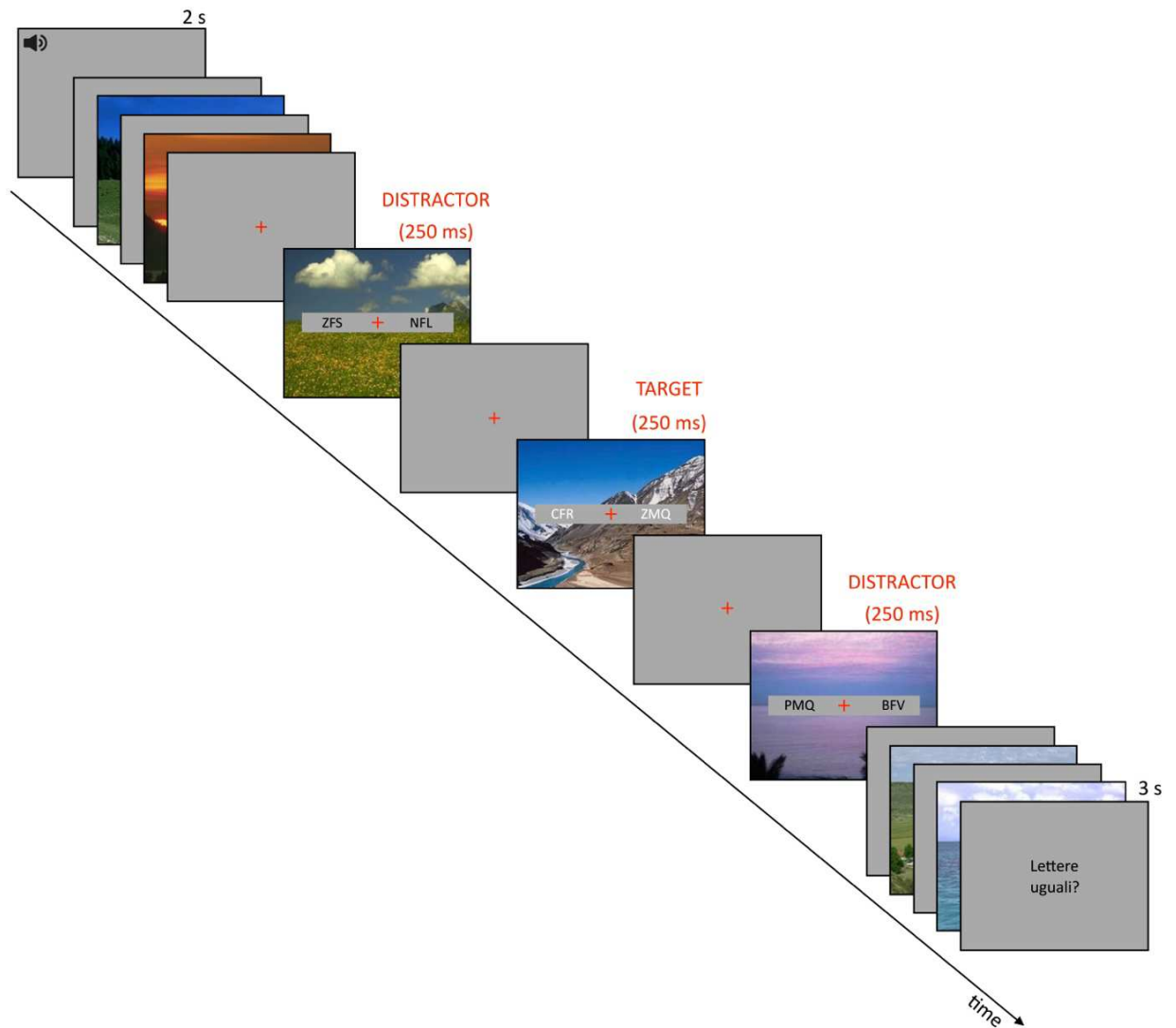


Figure 4.2 - Schematic of a letter matching task trial. Participants were sequentially presented with: a screen indicating the trial number (2 s), a fixation screen (500 ms), a stimulus display sequence in which display stimuli were presented at 250 ms/stimulus with an ISI of 500 ms (fixation screen) for a stimulus onset asynchrony (SOA) of 750 ms, with a response screen (3 s). In each trial, the image in the sequence position 4 was paired with an array of white letters (target).

Since only letters F and M were used as central letters of the two 3-letter clusters (except in the familiarization and in the catch trials of test phase, see *procedure* section), there were four possible combinations of those letters (named trial types), with two associated response types (*same* or *different*) (Table 4.1).

Central letter		Trial type	Response type
<i>Left</i> 3-letter cluster	<i>Right</i> 3-letter cluster		
F	F	FF	same
M	M	MM	same
F	M	FM	different
M	F	MF	different

Table 4.1 - Schematic of the stimuli, trial types and response types used in the letter matching task.

While performing the letter matching task, participants were also required to pay attention to and memorize the images presented in the background during the entire stimulus display sequence, because of the subsequent image recognition task⁶⁹.

IMAGE RECOGNITION TASK (SECONDARY TASK)

At the beginning of each trial, an auditory stimulus (250 ms) and a screen indicating the trial number (2 s) were simultaneously presented. Then, after a fixation screen (500 ms), a test image was presented for 2 s. After the presentation of the test image, a response screen ("*Have you already seen this image?*") appeared for 3 s, and then a next trial began (Figure 4.3).

The test image could be an *old* image (i.e., an image presented in one of the stimulus display sequences of the primary task) or a *new* image (i.e., an image never presented before). Participants were asked to make an old/new decision about each image.

⁶⁹ It should be pointed out that participants were told about the image recognition task before starting the experiment, since attention towards the secondary task stimuli (Swallow & Jiang, 2011; Leclercq & Seitz, 2012c) and an explicit secondary task (Leclercq & Seitz, 2012b) are two constraints for fast-TIPL to occur.

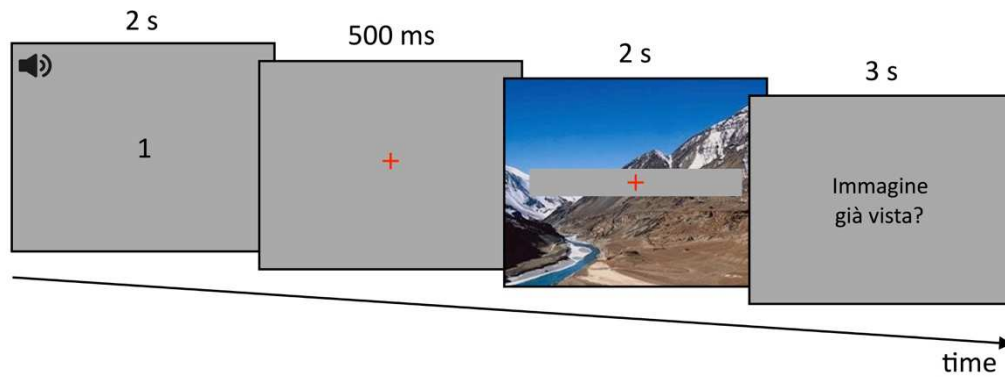


Figure 4.3 - Schematic of an image recognition task trial. Participants were sequentially presented with a screen indicating the trial number (2 s), a fixation screen (500 ms), a test screen (2 s) and a response screen (3 s).

For both tasks (the primary and the secondary task), participants gave their responses by marking the appropriate one of two possible responses, *yes* or *no*, on a response form which was provided individually at the beginning of the experiment. Participants were instructed to report each response at the time in which the response screen appeared⁷⁰.

(d) General procedure

The experiment lasted two consecutive days: in each experimental session, participants underwent first a familiarization, then a test phase (duration: approx. 1 hour/day). Two different image sets were used.

On each day, before starting the experiment, participants were provided with the response forms and they received both written and oral instructions.

FAMILIARIZATION

Before starting the experiment, participants were familiarized with the stimuli and the setup by performing one block. One block consisted of 9 trials of the letter matching task and of 12

⁷⁰ The request to wait for the response screen to appear before giving the response was extremely important in the letter matching task since participants had to pay attention to all the seven images presented in the display stimulus sequence in order to correctly perform the subsequent image recognition task.

trials of the image recognition task. The letter matching task trials and the image recognition task trials were not intermixed: the two tasks were performed in sequence (the letter matching task was performed first). The upper-case letters R and T (instead of F and M) were used as central letters of the two 3-letter clusters in the letter matching task.

TEST

Participants performed 8 blocks: each block consisted of 9 trials of the letter matching task and of 12 trials of the image recognition task. Blocks were separated by brief breaks.

In each experimental session, participants performed a total amount of 72 primary task trials, and 96 secondary task trials (Figure 4.4).

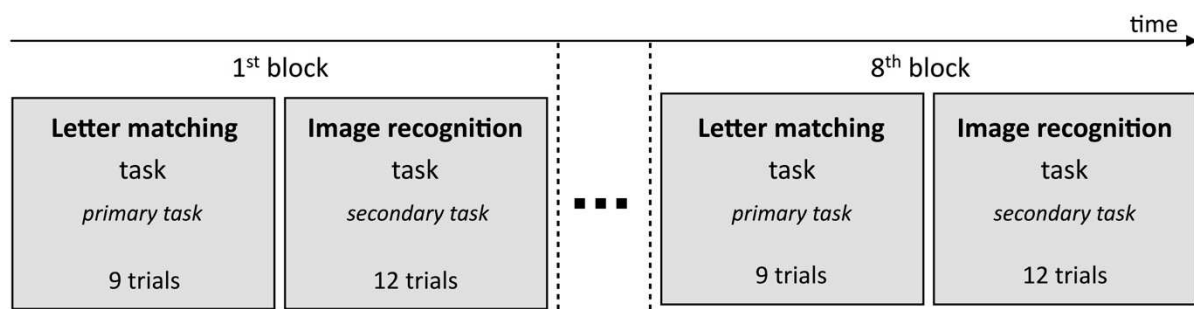


Figure 4.4 - Schematic of the procedure employed in the experiment. Each day, after being familiarized with the stimuli and the procedure, participants performed 8 blocks, each one consisted of 9 primary task trials, and 12 secondary task trials.

Letter matching task (primary task)

8 out of 72 primary task trials were catch trials (one catch trial/block): the upper-case letters C and G (instead of F and M) were used as central letters of the two 3-letter clusters of the target (the array of white letters). The catch trials were used in order to prevent a decrease in attention to the primary task due to the presentation of the same two letters (F and M) as central letters of the two 3-letter clusters for the entire duration of the primary task. The catch

trials were excluded from the analysis: a total amount of 64 primary task trials were therefore considered as valid trials.

The total amount of 64 primary task trials was divided into: 32 small- and 32 large-ILD condition trials. In each block, 4 small- and 4 large-ILD condition trials were presented in a randomized order.

In both small- and large-ILD conditions, participants performed: 9 F-F type trials, 9 M-M type trials and 14 F-M/M-F type trials, for a total amount of 18 trials associated with the response type *same* and 14 trials associated with the response type *different*. In each block, the three different trial types were presented in a randomized order.

For each participant, 4 d' were computed (Macmillan & Creelman, 2005): the d' relative to the performance in the small-ILD condition on Day 1 (d' -small-ILD-1), the d' relative to the performance in the large-ILD condition on Day 1 (d' -large-ILD-1), the d' relative to the performance in the small-ILD condition on Day 2 (d' -small-ILD-2) and the d' relative to the performance in the large-ILD condition on Day 2 (d' -large-ILD-2).

Image recognition task (secondary task)

Half of the test images (48 out of 96) were images previously paired with primary task stimuli (*old* images), while the other half were images never presented before (*new* images). In each block, 6 old and 6 new test images were presented in a randomized order.

16 out of the total amount of 48 old test images were images previously paired with the targets of the primary task (target-paired-image), while the other 32 test images were images previously paired with the distractors of the primary task (distractor-paired-image). 16 out of the 32 distractor-paired-image were images presented during primary task trials in sequence position 3 (before the occurrence of the target), while the other 16 distractor-paired-image were images presented in sequence position 5 (after the occurrence of the target). In other words, test images were selected⁷¹ from the pool of images presented during a primary task trial in sequence position 3 (distractor-paired-image), 4 (target-paired-image) and 5

⁷¹ The number of test images was established *a priori* (not all the images presented in association with the primary task stimuli in sequence positions 3, 4, and 5 were tested).

(distractor-paired-image). Images presented in sequence positions 1, 2, 6, 7 were never tested to avoid serial positions effects (the primacy or the recency effect).

Half of the total amount of 48 old test images (24 out of 48) were images previously paired with primary task stimuli of the small-ILD condition (8 target-paired-image; 16 distractor-paired-image), while the other half were images previously paired with primary task stimuli of the large-ILD condition (8 target-paired-image; 16 distractor-paired-image).

For each participant, 8 d' were computed (Macmillan & Creelman, 2005): the d' relative to the recognition of images previously paired with primary task targets of the small-ILD condition on Day 1 (d' -target-small-ILD-1), the d' relative to the recognition of images previously paired with primary task distractors of the small-ILD condition on Day 1 (d' -distractor-small-ILD-1), the d' relative to the recognition of images previously paired with primary task targets of the large-ILD condition on Day 1 (d' -target-large-ILD-1), the d' relative to the recognition of images previously paired with primary task distractors of the small-ILD condition on Day 1 (d' -distractor-large-ILD-1), the d' relative to the recognition of images previously paired with primary task targets of the small-ILD condition on Day 2 (d' -target-small-ILD-2), the d' relative to the recognition of images previously paired with primary task distractors of the small-ILD condition on Day 2 (d' -distractor-small-ILD-2), the d' relative to the recognition of images previously paired with primary task targets of the large-ILD condition on Day 2 (d' -target-large-ILD-2), the d' relative to the recognition of images previously paired with primary task distractors of the small-ILD condition on Day 2 (d' -distractor-large-ILD-2).

4.3.3 Data analysis

Data from participants ($n=12$) who did not perform the second session of the experiment (on Day 2) were excluded from the analysis because to comparing participants' performances between the two days of the experiment was one of the aims of the experiment.

Data from participants ($n=8$) who did not complete at least 64 out of 72 trials of the primary task and 88 out of 96 trials of the secondary task were excluded from the analysis because the number of valid trials was considered not sufficient in order to analyse the data.

Data from participants ($n=8$) who did not perform the two conditions of the primary task in a comparable fashion (i.e., participants whose performance in the primary task extremely

differed between the two primary task conditions) were excluded from the analysis because their performance was not considered reliable⁷².

A total of 87 participants met all the inclusion criteria (71 females; age range: 18-39).

Quantitative data are presented as average $d' \pm$ standard error of the mean (sem) or as average hit rate $\pm$ sem. Results were analysed for statistically significant differences by using repeated measures Analysis of Variance (ANOVA) and t-tests with Bonferroni correction.

4.3.4 Results

(a) Letter matching task (primary task)

The average d' across participants were: 0.756 ± 0.085 d' -small-ILD-1, 1.196 ± 0.107 d' -large-ILD-1, 0.893 ± 0.097 d' -small-ILD-2 and 1.564 ± 0.133 d' -large-ILD-2 (Figure 4.5; for individual data, see Supplemental Materials 3, Table S3.1).

⁷² For each participant, the variance between d' obtained in the large- and in the small-ILD condition was computed (separately for the two days of the experiment) by using the formula [$d'(\text{large-ILD}) - d'(\text{small-ILD})$]. Participants whose variance was more than ± 2 standard deviations (SD) from the average group's variance were excluded from the analysis.

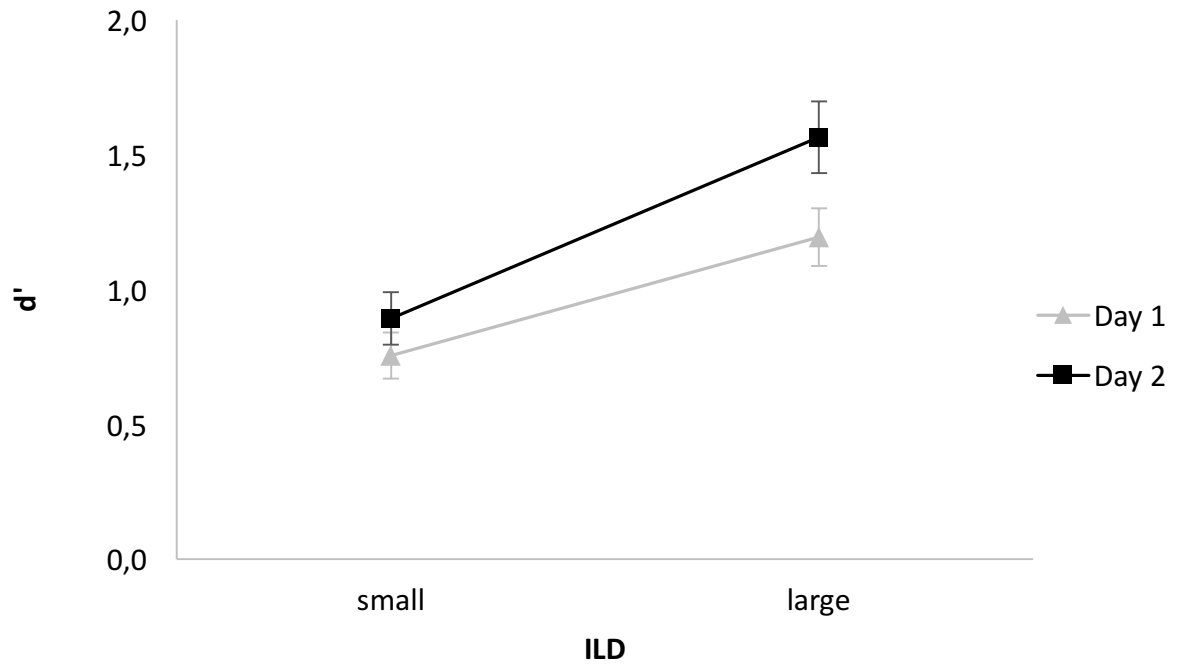


Figure 4.5 - Performance in the letter matching task. Average d' obtained in the small- and in the large-ILD conditions on Day 1 (depicted in grey) and on Day 2 (depicted in black) of the experiment are presented. Error bars represent the standard error of the mean (sem).

In order to test whether participants showed a difference in performance (1) between the two difficulty conditions of the primary task (the small- and the large-ILD conditions) and (2) between the two days of the experiment (Day 1 and Day 2), a two-way repeated measures ANOVA with the factors ILD (small, large) and Day (1, 2) was conducted. The results showed: (1) a main effect of ILD ($F[1, 86] = 51.138, p < 0.001$); (2) a main effect of Day ($F[1, 86] = 8.473, p = 0.005$); (3) a significant interaction between ILD and Day ($F[1, 86] = 1.170, p = 0.044$).

To further investigate the results, I performed the following comparisons by using paired t -tests: d' -small-ILD-1 vs d' -large-ILD-1, d' -small-ILD-2 vs d' -large-ILD-2, d' -small-ILD-1 vs d' -small-ILD-2, d' -large-ILD-1 vs d' -large-ILD-2. $P < 0.01$ was considered significant given the Bonferroni correction for repeated testing ($0.05/4 = 0.01$). Participants' performance in the two difficulty conditions of the primary task was influenced by the the phenomenon of crowding: participants performed better in the large- than in the small-ILD condition on both days (d' -small-ILD-1 vs d' -large-ILD-1, two-tailed paired t -test, $t[86] = -4.544, p < 0.001$; d' -small-ILD-2 vs d' -large-ILD-2, two-tailed paired t -test, $t[86] = -7.022, p < 0.001$). This result

suggested that I correctly manipulated the *task difficulty* variable by varying the distance between the central and the side letters of the two 3-letter clusters. Moreover, participants showed a significant learning (i.e., a higher d' on the second than on the first day of the experiment) in the large-ILD condition (d' -large-ILD-1 vs d' -large-ILD-2, two-tailed paired t-test, $t[86] = -3.425$, $p = 0.001$) but not in the small-ILD condition (d' -small-ILD-1 vs d' -small-ILD-2, two-tailed paired t-test, $t[86] = -1.374$, $p = 0.173$).

(b) Image recognition task (secondary task)

The average d' across participants are reported in Table 4.2 (for individual data, see Supplemental Materials 3, Table S3.2).

		ILD			
		small		large	
		target	distractor	target	distractor
Day	1	-0.156 (0.056)	0.040 (0.042)	-0.031 (0.050)	0.105 (0.037)
	2	-0.138 (0.068)	0.451 (0.046)	0.037 (0.071)	0.204 (0.043)

Table 4.2 - Display of the 8 average d' (sem) obtained in the image recognition task.

The observed d' were quite low (near or below zero in most cases) and they seem to indicate that recognizing the images presented during the primary task was extremely difficult, regardless of whether the images were previously paired with the targets or the distractors of the primary task⁷³.

⁷³ The d' presented in Table 4.2 have been considered reliable values because low d' values were consistent across participants (and not an exception) and because the sample was large (and not limited to few participants who might misunderstood the instructions).

In order to test whether participants showed a difference in the recognition performance between images previously paired with the primary task targets and distractors and to investigate whether this potential difference is modulated by the two difficulty conditions of the primary task and/or by the day of the experiment, a three-way repeated measures ANOVA with the factors Item (target, distractors), ILD (small, large) and Day (1, 2) was conducted. The results showed: a main effect of Item ($F[1, 86] = 68.304, p < 0.001$); no effect of ILD ($F[1, 86] = 0.560, p = 0.456$); a main effect of Day ($F[1, 86] = 12.517, p = 0.001$); a significant interaction between Item and ILD ($F[1, 86] = 10.182, p = 0.002$); a significant interaction between Item and Day ($F[1, 86] = 8.959, p = 0.004$); no interaction between ILD and Day ($F[1, 86] = 3.910, p = 0.051$); a significant interaction between all the three factors (Item, ILD, Day) ($F[1, 86] = 8.829, p = 0.004$).

In order to further explore the data and taken into account that d' were quite low, I decided to test first whether d' were higher than chance by testing those values against zero in 8 one-sample t-tests (chance level in d' analysis is defined as similar numbers of correct and erroneous responses, leading to $d'=0$; MacMillan & Creelman, 2005), and secondly to compare the d' relative to the recognition of images previously paired with the targets of the primary task to the d' relative to the recognition of images previously paired with the distractors of the primary task within each condition by using 4 paired t-tests. $P < 0.004$ was considered significant given the Bonferroni correction for repeated testing ($0.05/12 = 0.004$) (the same analysis was performed on hit rates, see Supplemental Materials 3, *Hit rate analysis*). The results of the one-sample t-tests showed that: d' relative to the recognition of images previously paired with the distractors of the primary task in the conditions small-ILD-2 and large-ILD-2 were significantly higher than chance (d' -distractor-small-ILD-2 vs 0, two-tailed one-sample t-test, $t[86] = 9.869, p < 0.001$; d' -distractor-large-ILD-2 vs 0, two-tailed one-sample t-test, $t[86] = 4.768, p < 0.001$); a tendency towards a statistical significant difference in the recognition of images previously paired with the targets of the primary task in the condition small-ILD-1 (d' -target-small-ILD-1 vs 0, two-tailed one-sample t-test, $t[86] = -2.773, p = 0.007$), which indicated a recognition performance lower than chance; a tendency towards a statistical significant difference in the recognition of images previously paired with the distractors of the primary task in the condition large-ILD-1 (d' -distractor-large-ILD-1 vs 0, two-tailed one-sample t-test, $t[86] = 2.811, p = 0.006$), which indicated a recognition performance

higher than chance. The other comparisons were not significant (d' -distractor-small-ILD-1 vs 0, two-tailed one-sample t-test, $t[86] = 0.940$, $p = 0.350$; d' -target-large-ILD-1 vs 0, two-tailed one-sample t-test, $t[86] = -0.619$, $p = 0.538$; d' -target-small-ILD-2 vs 0, two-tailed one-sample t-test, $t[86] = -2.030$, $p = 0.045$; d' -target-large-ILD-2 vs 0, two-tailed one-sample t-test, $t[86] = 0.522$, $p = 0.603$). The results of the paired t-tests showed: a significant difference in the recognition between images previously paired with the targets and the distractors of the primary task in the small-ILD condition on both days (d' -target-small-ILD-1 vs d' -distractor-small-ILD-1, two-tailed paired t-test, $t[86] = -2.923$, $p = 0.004$; d' -target-small-ILD-2 vs d' -distractor-small-ILD-2, two-tailed paired t-test, $t[86] = -7.551$, $p < 0.001$) (Figure 4.6); a tendency towards a statistical significant difference in the recognition between images previously paired with the targets and the distractors of the primary task in the large-ILD condition on Day 1 (d' -target-large-ILD-1 vs d' -distractor-large-ILD-1, two-tailed paired t-test, $t[86] = -2.816$, $p = 0.006$), while no difference was observed on Day 2 (d' -target-large-ILD-1 vs d' -distractor-large-ILD-1, two-tailed paired t-test, $t[86] = -2.176$, $p = 0.032$) (Figure 4.7).

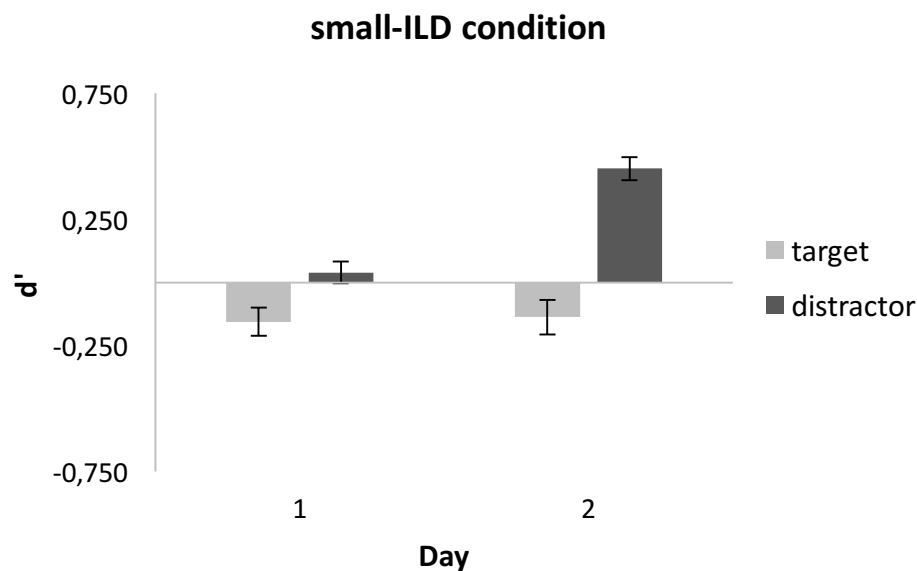


Figure 4.6 - Performance in the image recognition task for images paired with small-ILD condition stimuli. d' obtained for target-paired-images (depicted in light grey) and for distractor-paired-images (depicted in dark grey) are presented. Error bars represent the standard error of the mean (sem).

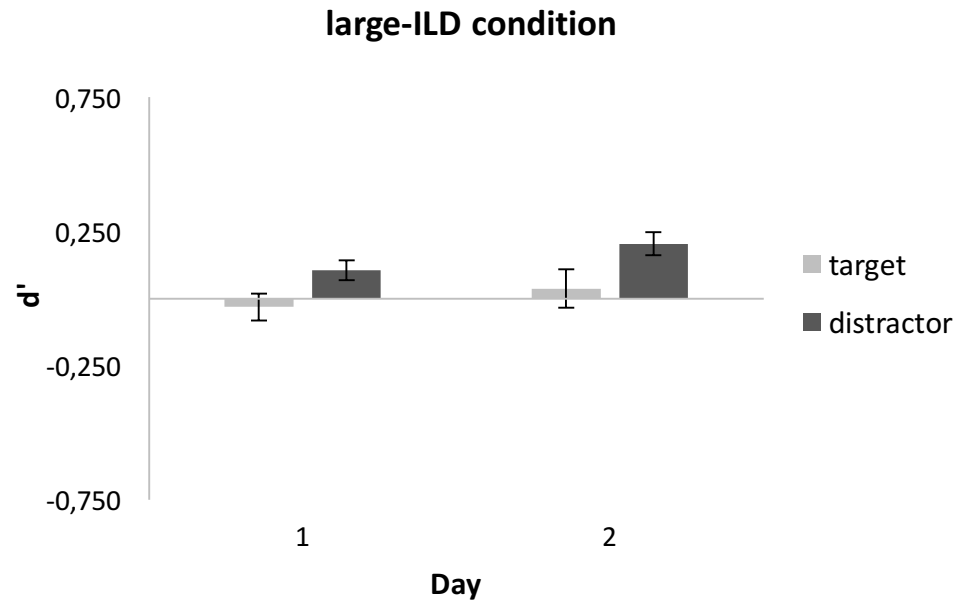


Figure 4.7 - Performance in the image recognition task for images paired with large-ILD condition stimuli. d' obtained for target-paired-images (depicted in light grey) and for distractor-paired-images (depicted in dark grey) are presented. Error bars represent the standard error of the mean (sem).

In the last analysis, I measured the response bias in order to verify whether participants were biased toward one response or the other (*yes* or *no* response). Table 4.3 reports the average values across participants of the bias measure c (*criterion*), computed as $\{-0.5 * [z(\text{Hits}) + z(\text{False Alarms})]\}$: c equal to zero indicates no bias, positive values of c indicate a participants' tendency to respond *no* (conservative response bias, in which the number of misses is higher than the false alarms), while negative values of c indicate a tendency to respond *yes* (liberal response bias, in which the number of false alarms is higher than the misses) (Macmillan & Creelman, 2005).

		ILD			
		small		large	
		target	distractor	target	distractor
Day	1	0.363 (0.049)	-0.083 (0.030)	0.288 (0.036)	0.301 (0.044)
	2	-0.127 (0.031)	0.411 (0.052)	0.618 (0.056)	0.535 (0.044)

Table 4.3 - Display of the 8 average c values (sem) obtained in the image recognition task.

A three-way repeated measures ANOVA with the factors Item (target, distractors), ILD (small, large) and Day (1, 2) was conducted. The results showed: a main effect of Item ($F[1, 86] = 249.994$, $p < 0.001$); no effect of ILD ($F[1, 86] = 0.755$, $p = 0.387$); a main effect of Day ($F[1, 86] = 140.842$, $p < 0.001$); a significant interaction between Item and ILD ($F[1, 86] = 8.746$, $p = 0.004$); a significant interaction between Item and Day ($F[1, 86] = 33.405$, $p < 0.001$); a significant interaction between ILD and Day ($F[1, 86] = 4.168$, $p = 0.044$); a significant interaction between all the three factors (Item, ILD, Day) ($F[1, 86] = 8.820$, $p = 0.004$).

Moreover, I performed the same 8 one sample t -tests and 4 paired t -tests used to analyse d' . $P < 0.004$ was considered significant given the Bonferroni correction for repeated testing ($0.05/12 = 0.004$). The results of the one-sample t -test analysis showed that the c value relative to the distractor-small-ILD-1 condition did not differ from chance (chance level = 0), namely no response bias was observed (c -distractor-small-ILD-1 vs 0, two-tailed one-sample t -test, $t[86] = -2.762$, $p = 0.007$), while c values relative to the other seven conditions differed significantly from chance (c -target-small-ILD-1 vs 0, two-tailed one-sample t -test, $t[86] = 7.366$, $p < 0.001$; c -target-large-ILD-1 vs 0, two-tailed one-sample t -test, $t[86] = 6.900$, $p < 0.001$; c -distractor-large-ILD-1 vs 0, two-tailed one-sample t -test, $t[86] = -4.093$, $p < 0.001$; c -target-small-ILD-2 vs 0, two-tailed one-sample t -test, $t[86] = 11.466$, $p < 0.001$; c -distractor-small-ILD-2 vs 0, two-tailed one-sample t -test, $t[86] = 7.864$, $p < 0.001$; c -target-large-ILD-2 vs 0, two-tailed one-sample t -test, $t[86] = 11.021$, $p < 0.001$; c -distractor-large-ILD-2 vs 0, two-tailed one-sample t -test, $t[86] = 12.181$, $p < 0.001$). The results of the paired t -tests showed a significant difference in c values between images previously paired with the targets and the

distractors of the primary task: in the small-ILD condition on both days (*c*-target-small-ILD-1 vs *c*-distractor-small-ILD-1, two-tailed paired t-test, $t[86] = 10.045$, $p < 0.001$; *c*-target-small-ILD-2 vs *c*-distractor-small-ILD-2, two-tailed paired t-test, $t[86] = 7.551$, $p < 0.001$); in the large-ILD condition on Day 1 only (*c*-target-large-ILD-1 vs *c*-distractor-large-ILD-1, two-tailed paired t-test, $t[86] = 13.453$, $p < 0.001$; Day 2: *c*-target-large-ILD-2 vs *c*-distractor-large-ILD-2, two-tailed paired t-test, $t[86] = 2.174$, $p = 0.032$).

Taken together, the results of the *c* analysis indicated that participants were mostly biased in their responses, with a general attitude towards a conservative response bias (with the following exceptions: in the condition distractor-small-ILD-1 no bias was observed; in the condition target-small-ILD-2 a tendency of a liberal response bias was observed), especially when they had to recognize images previously paired with the distractors of the primary task.

To recapitulate briefly, the results of the image recognition task suggest that the task was quite difficult to perform, that there was an overall advantage in the recognition of images previously paired with the distractors than with the targets of the primary task and that this advantage was higher for stimuli of the small- than of the large-ILD condition.

4.4 GENERAL DISCUSSION

The constraints necessary for fast-TIPL to occur are mainly four. One postulates that the presence of distractors in the primary task is mandatory (Leclercq & Seitz, 2011): the experiment here described met this constraint because the target of the primary task (the array of white letters) was presented among distractors (the arrays of black letters). Another constraint which was fulfilled was the one that requires the secondary task to be explicit (Leclercq & Seitz, 2012b): before the beginning of the experiment, participants were told to pay attention to the stimuli presented in the background during the primary task because they would be later asked to perform a task on those stimuli (the image recognition task). The experiment here presented used a delayed response paradigm which has been proven to not disrupt fast-TIPL even when an arbitrary stimulus-response mapping is used (Swallow & Jiang, 2010, Lin *et al.*, 2010). The last constraint is the one that claims that attention towards the

secondary task stimuli is needed for fast-TIPL to occur because it gates the learning of task-irrelevant stimuli paired with the occurrence of the primary task stimuli (Swallow & Jiang, 2011; Leclercq & Seitz, 2012c). The general aim of my experiment was closely linked to this constraint: in a dual-task condition, I investigated how much attention towards task-irrelevant (secondary task) stimuli is needed for fast-TIPL to be observed by modulating the attentional and cognitive load of the primary task.

I took advantage of the perceptual phenomenon of crowding and created two difficulty conditions of the primary task (the letter matching task) by varying the distance between target and flankers: according to the Bouma's law, the identification of a target becomes easier as the distance between target and flankers increases (Bouma, 1970). The two difficulty conditions of the primary task, named *difficult* (the small-ILD condition) and *easy* (the large-ILD condition), required respectively a high and a low attentional and cognitive load, which in turn determined a small or a large amount of attentional resources left to process the task-irrelevant stimuli presented in association with the primary task stimuli. The purpose of the study was thus to investigate either whether fast-TIPL could be observed even when the amount of attentional and cognitive load required by the primary task is significantly increased (namely the occurrence of a target of the primary task always causes an attentional boost which in turn enables fast-TIPL⁷⁴ to occur; Swallow & Jiang, 2010, 2011, 2012, 2013, 2014), or whether (and how) the amount of attentional and cognitive load required by the primary task, on the other hand, could impact on fast-TIPL (namely the learning of task-irrelevant stimuli is enabled when the amount of attentional and cognitive load required by the primary task is low and inhibited when it is high; Lavie & Tsal, 1994; Lavie, 2005). Moreover, the experiment was repeated in two consecutive days in order to investigate potential learning effects.

The results of the letter matching task indicated that I correctly manipulated the difficulty of the primary task: participants showed a better performance in the easy than in the difficult condition of the primary task (i.e., participants' performance in the two difficulty conditions of the primary task was largely influenced by the the phenomenon of crowding). Moreover, participants showed a significant learning effect in the easy but not in the difficult condition, which suggested that the difficult condition was quite demanding. As a consequence, I

⁷⁴ The term fast-TIPL always refers to the phenomenon of a better memorization of task-irrelevant information temporally paired with the occurrence of a target than of a distractor of the primary task.

assumed that the two tasks required a different attentional and cognitive load. When participants performed an easy primary task trial, a higher amount of attentional resources remained available to process task-irrelevant information rather than when they performed a difficult primary task trial.

The results of the image recognition task, on the other hand, indicated that recognizing the images presented during the primary task was extremely difficult, regardless of whether the images were previously paired with the targets or the distractors of the primary task. A slightly advantage was observed in the recognition of distractor-paired-images, especially on the second day of the experiment and in the recognition of images previously paired with a primary task stimulus of the difficult condition.

However, considering that the recognition performance in most of the cases did not differ from chance, I can only speculate about what determined the poor performance observed. It can be hypothesized that the amount of attentional and cognitive resources used to solve a primary task trial was so high, either in the difficult or the easy condition, that no resources were left available to process and encode the images presented with the occurrence of the primary task stimuli, irrespective of their identity (targets or distractors). In other words, it can be assumed that, in the course of the experiment, a massive dual-task interference occurred between the processing of primary task stimuli and the processing and encoding of task-irrelevant stimuli: the increase in the attentional and cognitive load required by the primary task determined not only a decrease but a complete depletion of attentional resources such as no other resources remained available to process the images.

In the present study, as stated in the previous paragraphs, I used two difficulty conditions of the primary task, which were supposed to determine a smaller or a larger amount of attentional resources left to process the task-irrelevant stimuli presented in association with the primary task stimuli. However, considering the poor performance in the recognition task, the amount of resources left after having performed the easy condition of the primary task can be considered not sufficient to give rise to the learning of the images. Moreover, bearing in mind that in most of the previous studies on fast-TIPL, data have shown a ceiling effect in participants' performances in the primary task, it would be interesting to hypothesize a third condition in addition to the two described (easy and difficult), where a simple matching task (without crowding) is proposed to participants. To be more precise, I hypothesize a condition

in which only two letters are displayed (respectively on the left and right of the central fixation cross) in association with each image, and participants have to say whether the two letters are the same or not. Without the use of flankers, the task will be easy to perform, but different from those typically used which account for an almost perfect performance (identification of a single letter). This experimental condition would help to identify whether it is simply an increase in the primary task condition which disrupts the learning of task-irrelevant stimuli, or whether, on the other hand, it is the difficulty intrinsic to the crowding phenomenon which determines the observed results.

CONCLUSIONS

For a time, neuroscientists asserted that there is a *critical period* in everyone's early life during which the brain goes through major changes. During this sort of temporal window, which was thought to be limited in nature, the brain is extremely plastic and this characteristic determines, besides other things, the acquisition of fundamental perceptual abilities (Hubel & Wiesel, 1964; Hensch, 2005). A vast amount of later research findings has proven evidence that, although it is true that a critical period exists, brain plasticity is not confined into this temporal window: brain plasticity occurs through the entire life (Livingston, 1966; Rakic, 2002). *Brain plasticity* is essential in order to learn new information and to adapt to the environment which constantly changes. However, there is a problem: the amount of information that a brain continuously receives from the environment is excessively huge to be entirely processed and learned. *Brain stability*, or in other words the ability of the brain to defend itself from needless information, is thus also essential. As a consequence, everyday human brains are facing the so-called *stability-plasticity dilemma*.

In the field of visual perception, it has been extensively demonstrated that the adult human brain is able to acquire new visual perceptual skills, which can last up to years, as a result of visual experiences: this process and its outcome are labelled *visual perceptual learning* (Fahle & Poggio, 2002). In simple terms, visual perceptual learning is learning to perceive: the visual system should learn to discriminate between important and unimportant information which are both present in the surrounding environment selecting the first and at the same time avoiding the last. Although the number of studies published on visual perceptual learning has grown enormously in recent years⁷⁵, it remains still not fully understood how the visual system selects behaviourally relevant information restricting the learning process to those information, or in other words how learning is gated in visual perception. However, visual

⁷⁵ Around 150 papers on visual perceptual learning were published in 2013 alone (source: Watanabe & Sasaki, 2015).

perceptual learning, which is considered a manifestation of visual plasticity (Gilbert, Li, & Piech, 2009), can be seen as a research tool through which investigate what gates visual plasticity.

A central issue in perceptual learning literature is whether attention is needed to gate learning. It has been argued that learning a stimulus is possible only when attention is directed towards that stimulus (Shiu & Pashler, 1992; Ahissar & Hochstein, 1993; Schoups, Vogel, Qian, and Orban, 2001). When attention is not directed to a stimulus, on the other hand, perceptual learning of that stimulus does not occur. The reasoning would seem to be flawless. However, in a ground-breaking study published in 2001, it was demonstrated for the first time that visual perceptual learning can occur in the absence of attention (Watanabe, Nanez, & Sasaki, 2001). However, this is not the whole story: the stimuli, which had been proven to be learned despite being unattended, were also task-irrelevant and presented at a level below the threshold of visibility, thus imperceptible.

After the reading of the previous paragraph, it would seem that there are two distinct types of visual perceptual learning: the task-relevant visual perceptual learning (TRPL), which occurs for attended and thus task-relevant supra-threshold stimuli, and the task-irrelevant visual perceptual learning (TIPL), which occurs for unattended, task-irrelevant and sub-threshold stimuli. In other words, it would seem that both an *active* and a *passive* type of visual perceptual learning exist, each one produced by independent mechanisms. However, this is not necessarily true. Recently, it has been proposed and successively tested the hypothesis that TRPL as well as TIPL are produced by the same mechanism and that they share the same underlying principles (Seitz & Watanabe, 2005; Shibata, Sasaki, Kawato, & Watanabe, 2016). If TRPL and TIPL are indeed two aspects of the same phenomenon, one cannot help but wonder why there is such a huge amount of conflicting findings between TRPL and TIPL studies regarding what gates learning, and in particular, regarding the role of attention. To reconcile these opposite findings, it is important to point out that there were a number of methodological differences in those studies which did or did not find TIPL: for example, the number and the spatial arrangement of the stimuli used during training differed. Another important distinction had to do with the visibility properties of the task-irrelevant stimuli: for example, in the study by Shiu and Pashler (1992), which found no evidence of TIPL, the task-irrelevant feature was presented at a supra-threshold level, while in Watanabe and colleagues

(2001), which did find evidence of TIPL, the task-irrelevant stimulus was presented at a sub-threshold level. In a first line of experiments, conducted at the Laboratory of Psychophysics (LPSY), Ecole Polytechnique Fédérale de Lausanne (EPFL), I tried to deepen the understanding about the mechanisms underlying visual perceptual learning by investigating whether perceptual learning can be produced by the exposure to a task-irrelevant, sub-threshold feature, even when during training participants attend and perform a task on another feature of a homologous stimulus to that used during test stages. Additionally, I examined whether TIPL is task-specific. The results provided further evidence for TIPL by showing that it occurs by the mere exposure to a task-irrelevant feature presented at a level that – at least at the beginning of the training – is sub-threshold, even when the same stimuli are displayed for the entire experiment. Moreover, I found that the visual perceptual learning yielded by the task-irrelevant and sub-threshold feature is task-specific, because it occurs only in the task for which participants received a specific training, and is not transferred to another task performed on the same stimulus.

Although the discovery of TIPL can be considered a milestone because it led to reassess the role of attention and task-relevance in visual perceptual learning and TIPL can be thus considered a useful research tool, it should be kept in mind that TIPL is a slow phenomenon: thousands of training trials are necessary in order to observe perceptual learning for unattended, task-irrelevant stimuli. However, a fast form of TIPL (fast-TIPL) has been recently studied in the context of perceptual memories accounting evidence of a learning mechanism similar to TIPL, but in which task-irrelevant stimuli are learned in a short time course (Lin, Pype, Murray, & Boynton, 2010). In a second study, I took advantage of a fast-TIPL paradigm which allowed me to study TIPL in a single experimental session. More specifically, I modulated the attentional and cognitive load required from the primary task in order to investigate how much attention towards task-irrelevant (secondary task) stimuli is needed for TIPL to be observed. The results showed that the increase in the amount of attentional and cognitive load required by our primary task impacted negatively on fast-TIPL: the learning of task-irrelevant stimuli was completely disrupted because no resources remained available to process those stimuli. In other words, a massive dual-task interference occurred between the processing of primary task stimuli and the processing and encoding of task-irrelevant stimuli. The interference occurred despite there were two different conditions of the primary task

which differed in the amount of attentive and cognitive load required to solve the primary task. This results seems thus to suggest that it is possible to observe fast-TIPL only when a small amount of attentive and cognitive resources is recruited in order to solve the primary task. In fact, in most of the previous studies published on fast-TIPL, data have shown a ceiling effect in participants' performances in the primary task, accounting evidence of a very easy to solve primary task.

To conclude, I would like to put emphasis on one crucial point: the purpose of the present dissertation was to explore the role of task-irrelevant information in visual perceptual learning, and by way of three different experiments I demonstrated that task-irrelevant stimuli can be learned or not learned. This occurred accordingly with the amount of attentive and cognitive load required by the task in which participants were engaged at the same time they were exposed to the task-irrelevant stimuli (primary task). When the primary task was very easy (as for example in Experiment 1) the task-irrelevant stimuli were learned, while they were not learned when the amount of attentional and cognitive resources required to solve the primary task was increased (as for example in Experiment 3). Although a direct comparison between the first study on TIPL (Chapter 2) and the second study on fast-TIPL (Chapter 4) is non appropriate because in those studies different stimuli and methodologies were used, the opposite role of attention in the two studies remains intriguing. Attention has been proven to prevent the learning of task-irrelevant features/stimuli in TIPL (Choi *et al.*, 2009; Tsushima *et al.*, 2008; Roelfsema *et al.*, 2010), while it is necessary to gate the learning of task-irrelevant stimuli in fast-TIPL (Swallow & Jiang, 2011; Leclercq & Seitz, 2012c): the results illustrated in the present dissertation confirm once again a different role of attention in TIPL and fast-TIPL. In fact, in the study on TIPL I used a task-irrelevant feature which was presented at a sub-threshold level, because previous studies have shown that TIPL does not occur for supra-threshold task-irrelevant stimuli (Shiu & Pashler, 1992). The use of a sub-threshold task-irrelevant feature determined the learning of that feature (TIPL) because the attentional system failed to detect and thus to suppress that feature. This result accounts further evidence of a negative role of attention in TIPL. In the study on fast-TIPL, on the other hand, task-irrelevant stimuli were presented at a supra-threshold level, because research on fast-TIPL have proven that fast-TIPL can be observed only when attention is directed toward the task-irrelevant stimuli (Swallow & Jiang, 2011; Leclercq & Seitz, 2012c). However, the use of a more

engaging primary task compared to those typically used in fast-TIPL research, determined a decrease of attentive resources which were still available to process the task-irrelevant stimuli. This result supports the idea that a high amount of attentional resources is needed to process task-irrelevant stimuli because the encoding process of those stimuli is gated by attention. This result, contrary to the previous one, accounts evidence of a positive and necessary role of attention in fast-TIPL. In other words, the difference between TIPL and fast-TIPL regarding the role of attention in these two learning mechanisms can be explained once again by analysing the properties of the task-irrelevant stimuli. When the task-irrelevant stimuli are task-irrelevant with respect to both the task (i.e., those stimuli can not be used to solve the primary task), and the participants (i.e., participants have not to perform a task involving the task-irrelevant stimuli), those stimuli have been proven to be distracting and attention inhibits them in order to perform the primary task (Tsushima *et al.*, 2008). This is the reason why in Experiment 1 I chose to use task-irrelevant stimuli presented at a sub-threshold level, and coherently with my expectation I found TIPL. When the task-irrelevant stimuli are task-irrelevant with respect to the task but not to the participants, as in fast-TIPL experiments, those stimuli are not distracting for the participants (i.e., participants have to perform a task involving those stimuli namely to memorize them) and attention is therefore necessary for the encoding of the task-irrelevant stimuli. In Experiment 3, I reduced the amount of attentional resources available to process the task-irrelevant stimuli which in turn determines no fast-TIPL, accounting evidence of a learning mechanism which required a high amount of attentional resources to be directed towards the task-irrelevant stimuli to be observed.

In conclusion, the results of my research suggest once again a different role of attention in TIPL and fast-TIPL, and at the same time support the idea that the crucial distinction that accounts for the differing role of attention in the two learning mechanisms can be found by analysing the properties of the task-irrelevant stimuli.

Supplemental Materials 1

Table S1.1 - Individual training data (Experiment 1).

Participant number	Luminance discrimination task						Slope
	d' session 1	d' session 2	d' session 3	d' session 4	d' session 5	d' session 6	
1	1.410	1.680	1.470	1.640	1.810	1.400	0.015
2	1.000	1.080	0.950	1.170	0.890	1.420	0.050
3	1.330	1.220	1.150	1.230	1.150	0.930	-0.061
4	2.100	1.640	1.800	2.080	2.030	2.220	0.059
5	0.640	0.740	0.600	0.840	0.620	0.560	-0.015
6	1.290	1.160	1.280	1.150	1.260	1.300	0.006
7	0.980	1.120	1.180	1.190	1.230	1.160	0.035
8	0.660	1.170	1.200	1.440	1.180	1.610	0.143
9	1.180	1.450	1.360	1.370	1.210	1.140	-0.026
10	1.920	1.860	2.120	2.200	2.360	2.540	0.134
11	1.340	1.380	1.230	1.610	1.270	1.349	0.003
12	1.680	1.500	1.690	1.660	1.920	1.664	0.033
13	0.810	0.830	0.960	1.200	1.300	1.315	0.119
14	1.060	1.430	1.490	1.600	1.660	1.776	0.125
15	1.090	1.170	1.310	1.280	1.230	1.203	0.020
16	1.380	1.630	1.770	1.810	1.690	1.562	0.032
17	1.000	1.010	1.300	1.250	1.390	1.360	0.083
18	0.840	1.440	1.060	1.190	1.110	0.910	-0.015
19	1.920	2.220	2.110	2.170	2.060	2.248	0.035
20	1.080	1.130	1.340	1.630	1.790	1.590	0.138
mean	1.236	1.343	1.369	1.486	1.458	1.463	0.046
sem	0.092	0.079	0.085	0.083	0.098	0.106	0.013

Table S1.2 - Individual data relative to the performance in the Vernier task (Experiment 1).

Participant number	Vernier task		
	PRE threshold	POST threshold	Pre-post change (%)
1	10.273	10.615	-3.3
2	22.263	8.330	62.6
3	18.983	16.433	13.4
4	13.245	12.788	3.5
5	23.068	10.618	54.0
6	12.228	9.770	20.1
7	22.260	8.368	62.4
8	31.755	26.018	18.1
9	14.743	15.548	-5.5
10	16.210	13.795	14.9
11	31.080	26.983	13.2
12	12.165	9.218	24.2
13	31.230	18.148	41.9
14	17.985	12.200	32.2
15	12.153	12.645	-4.1
16	11.860	12.235	-3.2
17	19.430	20.008	-3.0
18	25.550	21.525	15.8
19	18.415	16.948	8.0
20	15.060	8.385	44.3
mean	18.998	14.529	20.5
sem	1.523	1.260	5.0

Table S1.3 - Individual data relative to the performance in the bisection task (Experiment 1).

Participant number	bisection task		
	PRE threshold	POST threshold	Pre-post change (%)
1	21.508	27.690	-28.7
2	58.098	58.683	-1.0
3	54.815	34.748	36.6
4	61.805	67.498	-9.2
5	43.118	33.073	23.3
6	28.385	56.955	-100.7
7	60.273	36.978	38.6
8	59.470	49.173	17.3
9	40.290	46.608	-15.7
10	26.583	48.810	-83.6
11	44.858	36.263	19.2
12	39.118	27.433	29.9
13	41.313	52.610	-27.3
14	31.573	29.580	6.3
15	12.230	14.420	-17.9
16	33.278	33.305	-0.1
17	62.250	30.460	51.1
18	94.873	44.475	53.1
19	35.648	27.578	22.6
20	65.955	49.813	24.5
mean	45.772	40.307	1.9
sem	4.269	2.961	9.0

Supplemental Materials 2

Table S2.1 - Individual training data (Experiment 1).

Participant number	Luminance discrimination task						Slope
	d' session 1	d' session 2	d' session 3	d' session 4	d' session 5	d' session 6	
1	1.110	1.200	1.340	1.270	1.230	1.010	-0.014
2	0.600	0.790	1.500	1.360	1.570	1.120	0.137
3	1.670	1.950	2.030	1.920	1.930	2.090	0.055
4	0.860	1.000	1.100	1.410	1.080	0.960	0.030
5	1.110	1.200	1.430	1.440	1.580	1.590	0.101
6	1.160	1.080	1.050	1.200	1.130	1.030	-0.010
7	2.320	2.020	2.120	2.030	2.250	1.930	-0.039
8	1.120	1.390	1.400	1.680	1.870	1.720	0.135
9	1.150	1.210	1.270	1.310	1.100	1.500	0.042
10	1.070	0.890	0.940	1.020	1.060	1.080	0.018
11	1.610	1.530	1.410	1.760	1.860	1.650	0.044
12	1.390	1.790	1.840	1.770	2.120	2.350	0.163
13	1.800	1.800	1.690	1.770	1.910	1.680	-0.005
14	0.900	0.970	0.920	0.850	0.890	1.040	0.011
15	1.120	1.050	1.150	1.280	1.170	1.170	0.021
16	1.350	1.470	1.200	1.340	1.660	1.890	0.097
17	1.090	1.600	1.380	1.320	1.660	1.690	0.089
18	1.000	0.710	0.930	0.820	1.040	0.950	0.018
19	1.580	2.070	2.130	2.240	2.370	2.610	0.176
20	1.220	0.980	1.170	1.270	1.430	1.540	0.087
mean	1.262	1.335	1.400	1.453	1.546	1.530	0.058
sem	0.086	0.095	0.086	0.084	0.100	0.108	0.014

Table S2.2 - Individual data relative to the performance in the Vernier task (Experiment 2).

Participant number	Vernier task		
	PRE threshold	POST threshold	Pre-post change (%)
1	18.645	25.725	-38.0
2	19.518	12.880	34.0
3	18.718	17.768	5.1
4	23.608	32.875	-39.3
5	21.928	14.083	35.8
6	17.178	15.255	11.2
7	12.598	18.438	-46.4
8	25.278	17.223	31.9
9	23.405	29.073	-24.2
10	22.755	19.895	12.6
11	21.840	17.715	18.9
12	14.653	10.158	30.7
13	7.348	12.878	-75.3
14	25.500	27.620	-8.3
15	33.468	30.540	8.7
16	7.593	18.695	-146.2
17	13.463	8.013	40.5
18	24.785	8.563	65.5
19	14.460	19.373	-34.0
20	24.428	8.565	64.9
mean	19.558	18.267	-2.6
sem	1.451	1.681	11.4

Table S2.3 - Individual data relative to the performance in the bisection task (Experiment 2).

Participant number	bisection task		
	PRE threshold	POST threshold	Pre-post change (%)
1	40.423	35.578	12.0
2	36.003	25.200	30.0
3	68.235	39.628	41.9
4	48.245	43.495	9.8
5	29.970	39.343	-31.3
6	47.435	29.605	37.6
7	44.780	30.283	32.4
8	57.328	49.515	13.6
9	36.420	29.313	19.5
10	42.325	41.733	1.4
11	62.368	66.800	-7.1
12	27.248	28.960	-6.3
13	29.348	33.023	-12.5
14	68.500	67.450	1.5
15	27.863	20.223	27.4
16	36.978	27.830	24.7
17	36.865	46.595	-26.4
18	43.488	35.943	17.3
19	21.198	23.650	-11.6
20	18.600	23.490	-26.3
mean	41.181	36.883	7.4
sem	3.216	2.924	4.9

Supplemental Materials 3

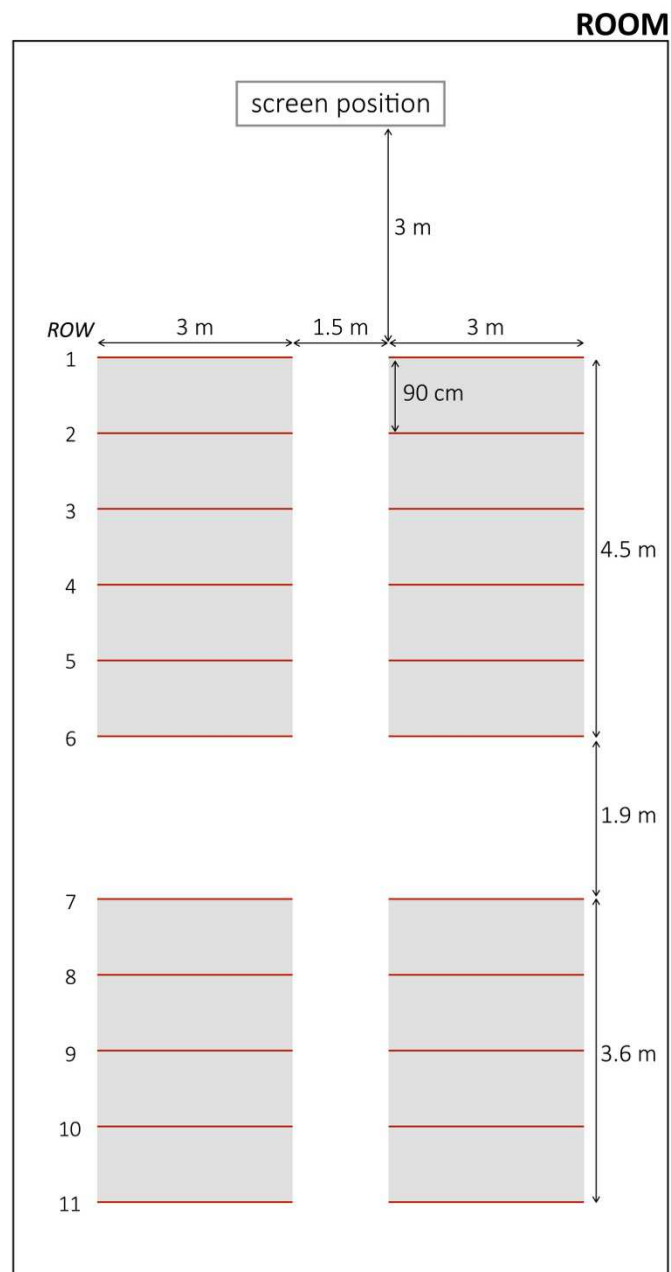


Figure S3.1 - Schematic of the experimental room and the arrangement of participants. Participants sat in correspondence of the 11 rows depicted as red lines with a minimum distance of 50 cm between each other.

Table S3.1 - Individual data relative to the performance in the letter matching task.

Participant number	Letter matching task (d')			
	small-ILD-1	large-ILD-1	small-ILD-2	large-ILD-2
1	0.797	2.230	4.121	5.055
2	0.876	2.527	1.938	3.117
3	0.648	2.388	0.509	1.465
4	0.431	-0.611	0.876	-0.176
5	0.506	0.000	0.366	1.556
6	1.763	0.928	0.785	0.792
7	1.747	2.230	0.785	2.958
8	1.326	0.997	0.701	2.433
9	0.282	1.350	1.222	1.832
10	0.040	0.956	0.426	0.589
11	0.084	0.366	0.135	-0.585
12	0.509	1.465	1.207	3.117
13	0.180	1.959	1.334	2.035
14	0.785	3.495	0.848	2.661
15	0.701	2.097	1.183	1.326
16	0.366	1.533	-0.040	1.498
17	-0.409	0.084	0.792	0.284
18	0.928	2.810	0.652	2.958
19	0.102	0.140	0.284	3.117
20	0.765	0.251	-0.065	-0.251
21	1.759	3.495	3.495	4.121
22	1.183	1.498	1.938	3.595
23	2.388	0.876	0.361	0.498
24	0.027	0.637	0.876	2.958
25	0.180	0.226	0.997	1.896
26	0.706	0.509	1.035	0.792
27	0.135	1.896	-0.102	1.222
28	0.284	0.637	0.027	0.701
29	-0.180	0.566	0.102	0.611
30	-0.366	1.207	1.498	0.084
31	0.180	-0.024	0.931	1.331
32	0.566	-0.284	0.251	-0.040
33	1.381	0.931	1.068	1.207
34	0.399	1.074	-0.399	0.648
35	0.785	0.876	-0.223	1.068
36	0.226	0.706	0.509	0.202
37	-0.251	0.226	0.361	1.183
38	0.431	0.637	0.135	0.797
39	2.433	1.787	2.433	2.385
40	3.292	2.288	2.035	3.319
41	2.667	3.117	0.135	0.284
42	-0.409	0.027	-0.655	0.027
43	1.498	0.931	0.769	1.605
44	0.792	1.498	2.527	1.657
45	1.605	0.931	0.652	2.230

Participant number	Letter matching task (d')			
	small-ILD-1	large-ILD-1	small-ILD-2	large-ILD-2
46	-0.128	0.934	2.527	2.433
47	1.832	2.159	3.058	3.495
48	0.251	0.040	0.931	1.465
49	0.648	0.648	0.652	1.183
50	0.928	1.222	2.527	2.958
51	0.652	0.785	1.183	1.035
52	0.027	1.938	1.307	4.121
53	0.765	0.431	1.657	1.657
54	0.462	1.350	1.465	0.931
55	0.202	0.100	1.222	2.055
56	2.055	3.058	3.058	4.121
57	0.648	2.230	1.074	1.498
58	0.785	0.997	0.478	1.381
59	1.759	1.334	0.848	1.832
60	0.706	0.648	0.785	0.769
61	1.381	3.117	1.222	2.230
62	1.556	1.381	1.498	2.230
63	1.465	1.326	1.307	0.245
64	-0.065	1.074	0.135	2.035
65	1.498	1.207	1.465	2.686
66	2.810	1.605	1.381	3.117
67	0.706	1.326	0.102	0.509
68	1.763	2.527	1.560	1.657
69	0.284	0.320	0.084	0.956
70	-0.084	-0.226	-0.506	-0.102
71	0.637	1.381	0.100	1.068
72	0.478	1.605	0.876	2.055
73	0.931	3.117	0.478	2.686
74	-0.848	0.140	-0.462	-0.797
75	0.765	-0.223	0.769	-0.462
76	1.326	1.498	1.183	2.035
77	0.431	0.785	0.366	0.931
78	-0.140	0.585	-0.040	0.284
79	0.498	2.230	0.934	2.958
80	0.102	1.560	0.848	0.509
81	1.035	-0.176	-0.431	0.226
82	0.509	0.431	-0.223	0.462
83	0.566	0.135	1.035	1.938
84	0.040	1.183	-0.282	0.706
85	-0.176	0.785	0.848	1.605
86	0.361	-0.140	0.361	-0.251
86	2.230	4.121	1.498	3.495
mean	0.756	1.196	0.893	1.564
sem	0.085	0.107	0.097	0.133

Table S3.2 - Individual data relative to the performance in the image recognition task (T=target; D=distractors).

Participant number	Image recognition task (d')							
	T-small-ILD-1	D-small-ILD-1	T-large-ILD-1	D-large-ILD-1	T-small-ILD-2	D-small-ILD-2	T-large-ILD-2	D-large-ILD-2
1	0.319	0.476	0.319	0.476	0.055	0.217	0.693	0.374
2	0.384	0.384	-0.993	0.384	0.649	-0.183	0.293	-0.183
3	0.000	-0.356	0.319	0.161	0.476	0.646	0.476	0.315
4	-0.161	-0.730	-0.993	-0.730	0.832	0.662	0.832	0.993
5	0.489	-0.186	0.489	0.489	-0.126	0.060	0.230	0.549
6	0.517	0.161	-0.832	0.331	-0.517	0.315	-0.161	0.315
7	-0.300	-0.115	-0.776	-0.513	-0.540	0.610	-0.064	-0.277
8	-0.570	-0.570	-0.214	-0.214	0.138	0.323	0.494	0.138
9	0.138	0.494	-0.338	0.138	0.000	0.476	0.000	-0.170
10	0.210	-0.108	0.529	0.053	0.319	0.637	0.637	0.161
11	0.052	0.371	-0.622	-0.266	0.356	0.186	0.000	1.163
12	-0.052	-0.052	0.266	0.266	0.476	1.308	0.476	0.662
13	-0.186	1.163	0.489	0.170	0.384	0.000	1.215	0.384
14	0.570	0.053	0.214	0.053	-1.715	0.970	0.494	0.138
15	-0.064	0.122	-0.064	-0.064	-0.183	0.649	0.293	0.293
16	-0.464	-0.108	-0.108	-0.108	0.549	0.230	-0.126	0.060
17	-1.308	-0.476	-0.832	-0.476	0.230	0.549	-0.126	-0.126
18	-0.662	0.331	0.170	0.331	-0.993	-0.993	-0.993	0.860
19	-0.622	-0.266	0.052	-0.437	-0.300	0.531	-0.300	-0.115
20	-0.338	0.323	0.812	0.812	0.000	0.186	0.000	-0.213
21	-0.064	0.292	0.610	0.292	-0.476	0.356	-1.853	0.000
22	-0.464	0.210	0.210	0.210	0.292	0.610	0.292	0.122
23	-0.540	-0.277	-0.064	0.122	0.000	0.832	0.000	0.662
24	-0.186	-0.186	0.170	-0.186	0.860	1.534	-0.993	1.045
25	0.264	0.583	0.264	0.583	0.000	0.000	0.000	0.000
26	-0.319	-0.157	-0.319	0.000	0.319	0.476	0.319	0.476
27	0.230	0.391	0.230	0.391	0.108	1.101	0.940	0.769
28	-0.214	-0.570	-0.570	-0.570	0.213	0.569	-1.640	0.213
29	0.264	-0.225	0.264	0.421	0.293	0.649	0.293	0.649
30	-0.410	0.421	-0.054	0.264	0.610	1.099	0.292	0.453
31	0.319	-0.170	0.000	0.476	-0.214	-0.053	-0.214	-0.570
32	-0.300	0.217	-0.300	0.217	0.549	0.391	-0.126	0.230
33	0.210	-0.464	-0.108	-0.108	0.138	0.323	-0.338	0.494
34	0.374	0.531	0.055	-0.115	0.583	0.421	-2.263	0.264
35	0.213	-0.263	-0.263	-0.263	0.138	0.494	-0.338	0.323
36	-0.776	-0.115	0.374	-0.300	-1.560	-0.183	0.293	0.293
37	0.000	0.000	0.637	0.000	-0.054	0.421	-0.410	0.107
38	0.157	0.476	-0.161	-0.331	0.423	0.742	-1.786	0.584
39	0.264	0.421	-0.410	0.753	0.230	0.706	-0.126	0.549
40	0.264	0.264	0.264	-0.225	-0.300	0.055	0.374	0.055
41	0.052	-0.437	0.727	0.371	0.112	0.273	0.749	0.588
42	0.464	-0.368	0.108	0.464	-0.423	0.570	0.214	-0.423
43	-0.356	0.000	0.000	0.161	-0.410	0.264	0.264	0.107
44	-0.064	0.122	-0.540	0.610	-0.096	0.566	0.736	0.167
45	-0.319	0.000	-0.319	0.000	0.112	0.749	-0.244	0.273

Participant number	Image recognition task (d')							
	T-small-ILD-1	D-small-ILD-1	T-large-ILD-1	D-large-ILD-1	T-small-ILD-2	D-small-ILD-2	T-large-ILD-2	D-large-ILD-2
46	0.583	-0.054	0.264	0.421	-0.410	0.264	-0.054	0.107
47	-0.371	-0.052	-0.727	0.266	0.292	-0.064	0.292	-0.064
48	-0.210	-0.529	-0.210	-0.053	0.112	0.431	0.749	0.112
49	0.054	-0.753	0.054	-0.264	-1.917	0.453	0.292	0.292
50	-1.269	0.371	0.108	0.371	-0.796	1.243	0.581	0.845
51	-0.423	-0.779	-0.423	-0.262	-0.476	-0.213	0.000	-0.860
52	0.000	0.161	-0.356	0.319	-0.244	0.273	0.431	0.749
53	-2.039	-0.186	-0.186	0.000	-1.269	0.584	1.258	0.371
54	0.112	0.431	0.112	-0.058	-1.715	0.494	-0.338	0.323
55	-0.161	0.157	0.157	0.646	-0.776	0.863	1.049	0.374
56	-0.186	0.170	-0.662	0.000	0.749	0.920	0.431	0.112
57	-0.161	0.157	0.476	0.157	-0.356	0.637	-0.356	0.000
58	-0.161	0.315	-0.517	0.000	-0.186	0.807	0.170	0.170
59	-0.157	-0.476	-0.157	0.161	-0.210	0.464	0.108	0.108
60	-0.319	-0.157	-0.319	-0.319	-0.570	0.423	-0.214	0.105
61	0.000	0.637	0.000	0.000	-1.786	-0.146	-0.409	0.067
62	0.067	0.584	0.742	0.067	-0.796	1.243	1.057	1.057
63	-0.796	0.198	0.581	0.845	0.000	0.000	0.000	0.000
64	-0.161	-0.161	-0.161	-0.517	-0.338	0.323	-0.338	0.323
65	-0.186	0.646	0.489	0.646	0.067	0.899	0.742	0.253
66	-2.039	0.489	-0.186	-0.186	-1.853	0.186	0.674	0.186
67	-0.108	-0.677	-0.108	0.053	-0.183	0.649	-1.560	0.080
68	-0.476	-0.213	-1.853	-0.213	-0.338	0.138	-0.338	-0.075
69	-0.266	0.052	0.727	0.727	-0.319	1.534	-0.319	0.319
70	-0.993	-0.637	0.356	0.356	0.264	0.421	0.583	-0.225
71	-0.052	0.437	0.266	0.437	0.356	0.186	0.356	0.000
72	-0.886	-0.054	-0.410	0.107	0.067	0.067	-0.409	0.253
73	-1.046	-0.214	0.423	0.423	-1.046	0.262	-0.214	-0.384
74	0.583	-0.054	-0.054	0.421	0.610	0.122	0.610	-0.277
75	0.476	0.646	0.157	0.157	0.266	0.266	-0.727	-0.210
76	0.319	0.319	0.000	-0.170	0.549	1.037	-0.126	0.060
77	1.203	-0.622	-0.266	-0.266	-0.186	0.331	0.170	0.489
78	0.055	-0.115	0.374	-0.513	0.230	-0.602	0.230	-0.339
79	-0.622	0.210	0.371	0.052	-0.300	0.531	-0.300	0.217
80	0.108	-0.210	-0.885	-0.210	0.157	0.315	-0.161	0.476
81	0.105	0.779	0.105	0.423	0.230	0.391	0.549	0.060
82	-0.054	0.107	0.583	0.421	0.000	0.000	-0.832	-1.215
83	-0.186	0.489	0.170	0.170	-1.377	0.662	0.000	0.476
84	-0.832	-0.170	-0.356	0.000	0.423	0.262	-0.570	-0.214
85	0.583	0.107	-0.410	0.264	0.052	0.541	-0.266	-0.105
86	-0.126	0.391	0.230	0.549	0.213	0.398	0.887	0.213
86	-0.570	0.105	0.105	-0.384	-0.720	1.318	0.749	0.749
mean	-0.156	0.040	-0.031	0.105	-0.138	0.451	0.037	0.204
sem	0.056	0.042	0.050	0.037	0.068	0.046	0.071	0.043

Hit rate analysis

Typically, studies on fast-TIPL report only the hit rates (and the false alarms rates) relative to the performance in the recognition task without computing the d' . In order to analyse the data as most fast-TIPL studies did, I computed the hit rates separately for images previously paired with the targets and the distractors of the primary task, for each one of the four conditions (small-ILD-1, large-ILD-1, small-ILD-2 and large-ILD-2). The hit rates were computed as $[(\text{Hits} + \text{Correct Rejection})/\text{number of trials}]$ because the hit rate corresponds to the proportion of *yes* responses when an *old* stimulus is presented [hit rate = $P(\text{"yes"} \mid \text{old-stimulus})$]. The average hit rate (%) across participants are reported in Table 4.4.

		ILD			
		small		large	
		target	distractor	target	distractor
Day	1	36.1 % (2.0 %)	41.1 % (1.6 %)	39.7 % (1.8 %)	43.5 % (1.7 %)
	2	28.1 % (1.9 %)	44.3 % (1.9 %)	32.4 % (1.9 %)	34.8 % (1.5 %)

Table 4.4 - Display of the 8 average hit rates (sem) obtained in the image recognition task (the average false alarms rates⁷⁶ were 39.6 ± 1.3 % and 28.2 ± 1.3 % respectively on Day 1 and Day 2).

A three-way repeated measures ANOVA with the factors Item (target, distractors), ILD (small, large) and Day (1, 2) was conducted. The results showed: a main effect of Item ($F[1, 86] = 58.437$, $p < 0.001$); no effect of ILD ($F[1, 86] = 0.038$, $p = 0.846$); a main effect of Day ($F[1, 86] = 15.304$, $p < 0.001$); a significant interaction between Item and ILD ($F[1, 86] = 14.679$, $p < 0.001$); a significant interaction between Item and Day ($F[1, 86] = 6.401$, $p = 0.013$); a significant interaction between ILD and Day ($F[1, 86] = 8.658$, $p = 0.004$); a significant

⁷⁶ False alarms rate was computed as $[(\text{False Alarms} + \text{Misses})/\text{number of trials}]$ because the false alarms rate corresponds to the proportion of *yes* responses when a *new* stimulus is presented [hit rate = $P(\text{"yes"} \mid \text{new-stimulus})$].

interaction between all the three factors (Item, ILD, Day) ($F[1, 86] = 12.614, p = 0.001$).

Moreover, I performed the same one sample t-tests and paired t-tests used to analyse d' . $P < 0.004$ was considered significant given the Bonferroni correction for repeated testing ($0.05/12 = 0.004$).

The results of the one-sample t-tests showed that the hit rates (H) relative to each one of the eight conditions differed significantly from chance (chance level = 50%; H-target-small-ILD-1 vs 50%, two-tailed one-sample t-test, $t[86] = -7.100, p < 0.001$; H-distractor-small-ILD-1 vs 50%, two-tailed one-sample t-test, $t[86] = -5.654, p < 0.001$; H-target-large-ILD-1 vs 50%, two-tailed one-sample t-test, $t[86] = -5.691, p < 0.001$; H-distractor-large-ILD-1 vs 50%, two-tailed one-sample t-test, $t[86] = -3.910, p < 0.001$; H-target-small-ILD-2 vs 50%, two-tailed one-sample t-test, $t[86] = -11.784, p < 0.001$; H-distractor-small-ILD-2 vs 50%, two-tailed one-sample t-test, $t[86] = -2.955, p < 0.001$; H-target-large-ILD-2 vs 50%, two-tailed one-sample t-test, $t[86] = -9.160, p < 0.001$; H-distractor-large-ILD-2 vs 50%, two-tailed one-sample t-test, $t[86] = -9.979, p < 0.001$).

The results of the paired t-tests showed: no difference in the recognition between images previously paired with the targets and the distractors of the primary task in the small-ILD condition on Day 1 (H-target-small-ILD-1 vs H-distractor-small-ILD-1, two-tailed paired t-test, $t[86] = -2.478, p = 0.015$) and a significant difference on Day 2 (target-small-ILD-2 vs distractors-small-ILD-2, two-tailed paired t-test, $t[86] = -8.410, p < 0.001$); Moreover, on both days, no difference in the recognition between images previously paired with the targets and the distractors of the primary task in the large-ILD condition was found (H-target-large-ILD-1 vs H-distractor-large-ILD-1, two-tailed paired t-test, $t[86] = -2.426, p = 0.017$; H-target-large-ILD-2 vs H-distractor-large-ILD-2, two-tailed paired t-test, $t[86] = -1.310, p = 0.194$). To briefly recapitulate, the results of the one-sample t-tests on hit rates did not perfectly match those observed in the d' analysis. However, the results of the paired t-tests on hit rates, which had more relevance to the purpose of the experiment, confirmed those observed in the same analysis performed on d' .

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