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Retroactive Transfer Phenomena in Alternating User Interfaces

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ABSTRACT

Given the ubiquitous nature of interactions across applications and systems, users often need to alternate between devices, software, or techniques to complete a single task. In this thesis, I investigate retroactive transfer when users alternate between different interfaces. Retroactive transfer is the influence of a newly learned interface on users' performance with a previously learned interface. I explore the theoretical and psychological foundations behind learning, skill acquisition, and transfer of skill to better characterize the retroactive transfer phenomenon.

In an interview study, participants described their experiences when alternating between different interfaces, e.g. different operating systems, devices, or techniques. Negative retroactive transfer related to text entry was the most frequently reported incident. I then report on a laboratory experiment that investigated the impact of similarity between two keyboard layouts, and the number of alternations between them, on retroactive interference. Results indicate that even small changes in the interference interface produced a significant performance drop for the entire previously learned interface. The amplitude of this performance drop decreases with the number of alternations.

Based on the findings of this thesis, the retroactive transfer should receive more attention by designers in Human-Computer Interaction (HCI). Their interfaces should be more systematically evaluated not only for intramodal learning and proactive transfer but also for retroactive transfer.

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1 INTRODUCTION

We live in a world surrounded by an abundance of digital interactive systems designed to assist or automate human tasks and activities. Interactive systems drastically changed the way people act and interact in everyday life. They changed how people access services through mobile devices, large displays, augmented Reality, etc.

Human **C**omputer **I**nteraction (HCI) is a multidisciplinary field of study, focusing on the design, evaluation and implementation of interactive systems. It also investigates the action-perception loop between the user(s) and interactive system(s). Interaction with a computer is a type of a communication. Users receive computers' output in the form of perceptual information and respond by providing input to the computer using keyboards, mice, and other interactive devices.

In this context, it is important to understand how the users develop skills to learn, adopt and use interactive systems. Subsequently, to benefit from these interactive systems people must acquire knowledge and learn necessary *skills*. A skill is a learned and goal-oriented activity which is directed toward the attainment of a specific goal. For instance, to benefit from word processing interfaces, e.g. Microsoft Word, the users must learn how to type using a keyboard layout.

Given the ubiquitous nature of interaction, users often need to alternate between devices, software or techniques to complete a single task. For instance, they can regularly alternate keyboard layouts, operating systems (e.g., Mac vs. Windows) or software applications (e.g., Keynote vs. PowerPoint). Concerning the variety of systems, one question is how users adapt from one interface to another one? How quickly will users learn, adopt and master a novel interface given their previous experience? How will learning a new interface influence one's the expertise with previously learned interfaces? The key concept underlying these questions is skill transfer. Skill transfer is the influence of learning one skill on the performance of another skill.

Transfer can be classified as either proactive transfer or retroactive transfer. Several studies investigated *proactive* (Figure 1) transfer from a previously learned interface to a new interface (Jokinen et al., 2017; Ramesh et al., 2011b; Scholtz and Wiedenbeck, 1990a), for instance, how quickly users can master the new AZERTY key-

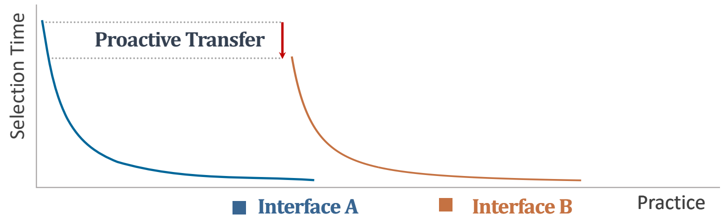

Figure 1: Conceptual model of proactive transfer, which is the influence of previously learned interface A (e.g., QWERTY keyboard layout) on the learning of new interface B (e.g., AZERTY keyboard layout)

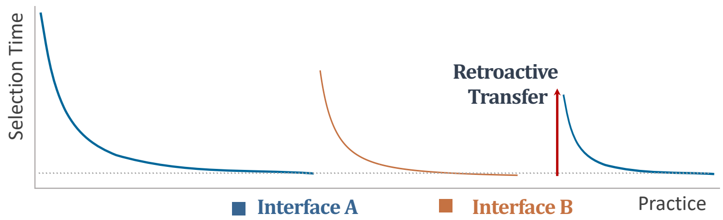

Figure 2: Conceptual model of retroactive transfer, which is the influence of a newly learned interface B (e.g., AZERTY) on the retention of a previously learned interface A (e.g., QWERTY)

board layout after mastering the previously learned QWERTY layout. However, proactive transfer neither captures the return to the original layout, i.e. the influence of the new AZERTY on the continuous learning of the QWERTY keyboard, nor the effect of regularly alternating between the two practiced layouts. **Retroactive transfer** (Edwards, 2010; Schmidt and Lee, 1988) is the influence of a *newly* learned skill on the retention of a *previously* learned skill (Figure 2).

Retroactive transfer has been investigated in cognitive psychology (Bunch, 1946; McGeoch and Irion, 1952; Osgood, 1949). However, in contrast with proactive transfer, retroactive transfer has received much less attention in HCI. It is not clear what is the impact of alternating between interfaces. It is of critical importance because it is frequent and is likely to be even more frequent with the increasing number of devices, systems and interactive contexts.

Given the ubiquitous nature of interaction, it would be dramatic if learning a novel interface had a negative impact on a previous learned interface we are likely to continue to use. Therefore, maintaining previously acquired skill sets is crucial when learning how to use new interfaces. This thesis addresses the conditions under which retroactive transfer occurs and investigates the impact of retroactive transfer on performance when using different interfaces.

1.1 RESEARCH GOAL

The long-term goal (that I do not address in this thesis) is the design of interfaces that better support alternations. Accordingly, the main goal of this thesis is to understand the retroactive transfer phenomena in HCI context. The aim is to better understand how alternating between interfaces influences users'performance. This main goal can be divided into more concrete subgoals:

> **RG1**: Identify HCI scenarios in which retroactive transfer (potentially) occurs and understand the specifics of these scenarios.
>
> **RG2**: Identify the factors that play a role in retroactive transfer
>
> **RG3**: Quantify the impact of these factors on performance.
>
> **RG4**: Provide recommendations and future research directions.

1.2 RESEARCH APPROACH

My work includes the following general approaches:

1. THEORETICAL APPROACH. I used concepts, theories and models in cognitive psychology to (1) better understand the learning process and skill acquisition which are necessary to introduce retroactive transfer, and (2) identify the main factors involved in retroactive transfer.

2. EMPIRICAL APPROACH
   Qualitative methods : interview & introspection
   I completed an Introspection[1] through my personal experience with using text entry. I also conducted an interview-based study to understand user experiences when alternating between interfaces (e.g., devices, applications, operating systems). This helped me to identify the main tasks that produce interference.

   Quantitative methods: Controlled lab experiment
   I conducted a controlled experiment to investigate retroactive interference when users alternate between interfaces

[1] Introspection involves examining one's own thoughts, feelings and sensations in order to gain insight.

and how the similarity between them affects the magnitude of such interference. The experimental design builds on standard motor learning experiments of retroactive transfer, but is extended to cover multiple alternations and to apply to a user interface context.

1.3 APPLICATION DOMAIN

For most interactive systems, users interact via text entry devices such as a keyboard. I focus on text entry in this thesis because it is one of the most common ways to perform HCI tasks. There are several contributions in terms of interaction techniques, empirical studies, models of performance and optimization methods in the field of text entry. Moreover, in the qualitative study participants suggested that alternating between keyboard layouts is a common cause of retroactive interference.

1.4 CONTRIBUTIONS

- I transpose concepts, theories and models from cognitive psychology to HCI.
- I report findings from two rounds of interviews and a controlled experiment, that increase our understanding of retroactive interference while using interactive systems in a HCI context.
- I provide recommendations and subsequent research directions in consideration of retroactive transfer in HCI.

1.5 THESIS STATEMENT

I believe that retroactive transfer should receive more attention in HCI, as the ubiquitous nature of interactions across applications and systems requires users to alternate between similar interfaces quite often. Thus, measuring and understanding the factors contributing to retroactive transfer can give clues to how interfaces such as soft keyboards should be designed with transfer and interference in mind.

1.6 THESIS OVERVIEW

The rest of this thesis is organized as follows:

Chapter 2: I present a discussion of the role of memory in learning from cognitive and psychology point of view.

I describe cognitive processes involved in learning that occur in defined memory's systems. Then, I outline the major types of long-term memory and describe how information is encoded and organised in long-term memory. Finally, I explain how forgetting occurs, and discuss the underlying causes of forgetting such as memory decay, retrieval failure and interference.

Chapter 3: I summarize related work in skill acquisition and provide definitions, factors, theories and models in cognitive psychology literature. I start by introducing skill and discuss the main characteristics of a skill. Then, I describe skill acquisition in form of different stages, and present the three-stage models of Fitts and Posner (Fitts and Posner, 1967). I discuss the basic laws and fundamental principles of learning, such as the power law of practice. At the end, I present different interactive techniques designed to facilitate skill acquisition and improve user's performance while performing text entries' tasks.

Chapter 4: I focus on skill transfer in this chapter. I follow the same structure of the previous chapter and discuss definitions, factors, theories and models in cognitive psychology literature. First I distinguish transfer from one skill to another skill or to the same skill from one context to another one. Then, I categorize transfer of skill as positive and negative transfer; and proactive and retroactive transfer. I discuss retroactive transfer and the related concepts, as well as the factors influencing retroactive transfer. These factors are inspiring for designing the controlled experiment described in Chapter 6. The theory of identical elements and other theories representing the reasons behind transfer are also presented in this chapter.

Chapter 5: I describe two rounds of interview with potential users who face retroactive interference while working with different interfaces. The first round of interview was conducted to understand the retroactive transfer phenomena when using interactive systems. The second round of interview focuses explicitly on keyboard usage. Since participants suggested that alternating between keyboard layouts is a common cause of retroactive interference; the severity of which is attributable to the degree of similarity between them.

Chapter 6: I present the experimental design to study retroactive transfer in a laboratory controlled experiment. I explain the experimental rational and the operationalization process to study a complex phenomena with the constraints of a laboratory experiment. In particular, I justify the choice of the factors based on the findings of Chapter 4 and Chapter 5.

Chapter 7: I report the result of the user experiment focusing on Intramodal Improvement, proactive transfer, retroactive transfer in first alternation and retroactive transfer in second alternation. The results show that having a small changes in the key' positions of interference interface is sufficient to produce a significant performance drop for the entire interface.

Chapter 8: I provide a summary of this thesis' contribution, discusses the limitation and give directions for future work.

Part I

THEORETICAL FOUNDATIONS

Chapter 2 includes a comprehensive introduction to the foundation of psychology and cognitive sciences regarding human memory process in learning and forgetting. The aim of this chapter is to provide theoretical foundations to study the phenomena related to skill acquisition in Chapter 3 and transfer of skill in Chapter 4.

Chapter 3 is dedicated to summarizing previous works concerning skill acquisition. Finally, Chapter 4 provides a general overview of transfer of skills and focuses on retroactive interference in psychology; a phenomenon that is not well-investigated in HCI. Altogether, this part contributes toward a better understanding of retroactive transfer's phenomena.

2 MEMORY: LEARNING AND FORGETTING

This chapter offers a general overview of the foundation of psychology and cognitive sciences regarding memory process in learning and forgetting. This will be useful to understand the mechanisms involved in retroactive transfer. This chapter begins with describing different memory systems involved in the process of encoding, storage and information retrieval. The second part discusses the underlying causes of forgetting such as memory decay, retrieval failure and interference.

2.1 LEARNING

Learning is the process of acquiring knowledge (Gross, 2015). The psychology of learning concerns how people learn and interact with their environments. For learning to occur, it's critical that incoming information is processed within the brain. The information processing theory holds that humans actively process the information they receive from their senses and focuses on the flow of information through the cognitive systems (Card, 1983). The information processing approach is to characterize humans as an information processing systems (like a computers), which encode input, operate on that information, store and retrieve it from memory, and then produce output in terms of actions.

In the past several decades, a number of psychological models (Anderson, 2009a; Anderson et al., 1997; Atkinson and Shiffrin, 1968; Card, 1983; Fitts and Posner, 1967; Howes and Young, 1997; Kieras and Meyer, 1997; Lindsay and Norman, 1977; Newell, Simon, et al., 1972) have been developed to represent the aspects of human information-processing as a task is being performed. The most widely used architecture in the psychology is the modal model, an adapted version of the Atkinson and Shiffrin model (Atkinson and Shiffrin, 1968). Figure 3 represents the modal model with the distinct memories, positioned between input and output. This model is predicated on the metaphor of the mind as a computer.

Among the psychological models, there are some models that can be applied to HCI. The Model Human Processor (MHP)[1] (1983) (Card, 1983) is a well-known model in this domain. MHP

[1] It is also known as CMN model. It takes the name after its creators Stuart **C**ard, Thomas P. **M**oran and Allen **N**ewell.

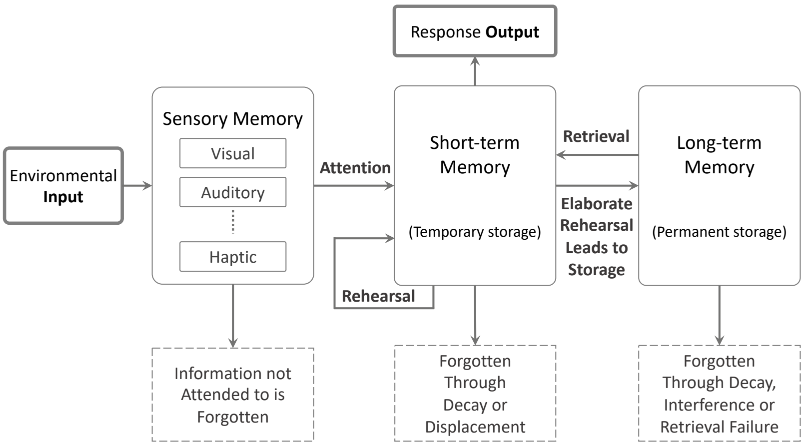

Figure 3: The modal model. The conceptualised flow of information through the memory system, adapted from (Atkinson and Shiffrin, 1968, 1971)

is a general characterization of human information processing. It can be described as a set of processors: perceptual, cognitive, and motor, and their associated memories, as well as their interactions that operate based on a set of principles, see Figure 4. The goal of this model is to calculate cognitive and motor processing time. However other more recent models, including the adaptive control of thought (ACT-R) Model (1997) (Anderson et al., 1997), the State, Operator, and Result (SOAR) Model (1997) (Howes and Young, 1997), and the EPIC Model(1997) (Kieras and Meyer, 1997) have considerable utility for the HCI field.

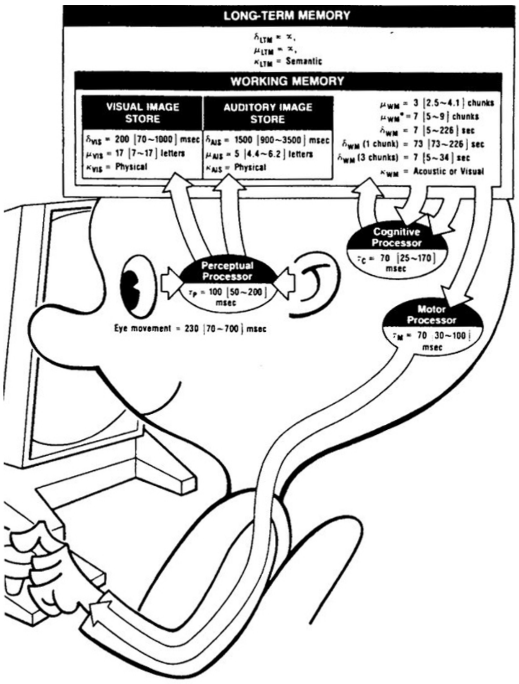

Figure 4: The Model Human Processor; memories and processors (Card, 1983).

A complete survey of human models is out of the scope of the present work (see (Gray and Altmann, 2001; Norman, 2013) for more details). Nonetheless, I provide here a brief overview of some of the main common concepts. I aim to illustrate cognitive processes involved in learning that occur in defined memory's systems (i.e., sensory memory, short-term memory and long-term memory). Most of the models, such as MHP (Figure 4), EPIC (Figure 5) and the modal model (Figure 3), are based on the assumption that the processing between stimuli and responses consists of a series of discrete systems for which the output for one system serves as the input for the next.

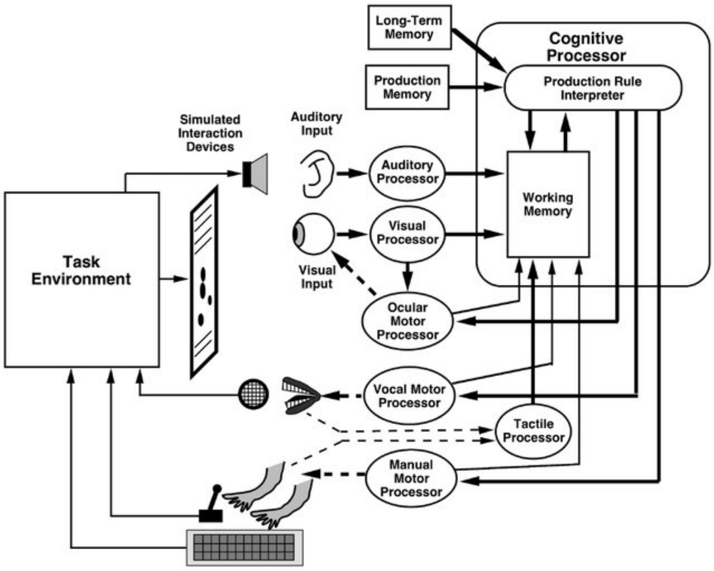

Figure 5: The high-level overview of the EPIC cognitive architecture, (Kieras and Meyer, 1997).

2.2 MEMORY

Memory is an essential cognitive process to encode, store, retain, and later retrieve the information we have learned or experienced (Shiffrin and Atkinson, 1969). In order to form new memories, the perceived information by sensory modalities[2], must be changed into a usable form, which occurs through the process known as encoding. Once the information has been successfully encoded, it must be stored in memory for retrieving and later used.

While several different human memory systems have been proposed, the memory system called *modal model* initially proposed by Atkinson and Shiffrin (Atkinson and Shiffrin, 1968) (Figure 3)

[2]The term sensory modality is often used interchangeably with sense. The basic sensory modalities include: light, sound, taste, temperature, pressure, and smell (Small and Prescott, 2005)

is often used to explain the basic structure and function of memory. It is comprehensive enough to provide a basic foundation for thinking about memory. Around 50 years after its first publication, it is still influential in the development of cognitive psychology (it has been cited over 11,000 times, as of October 2020, source: Google Scholar). This model divides human memory into three distinct systems: sensory memory, short-term memory, and long-term memory. In overall, when mentioning memory system (sensory, short-term and long-term memory), we intend to characterize the storage in which the memory resides. Unlike the system, processing views concentrate on the type of processing involved in memory. These two views are not mutually exclusive. There are different memory systems and how the information is processed within that particular system will influence how the memory is encoded, retrieved, etc. Below I focus on different memory systems and different types of processes within those systems.

2.2.1 *Sensory Memory*

When a stimulus (e.g., visual or auditory) is presented, it leaves a sensory trace of that stimulus in the brain. A memory trace, also know as an *engram*, is a means by which information is stored as physical or biochemical change in the brain in response to external stimuli (Ryan et al., 2015). For example, the ability to look at something and remember what it looked like with just a second of observation is an example of sensory memory. Sensory memory is very brief and its purpose is to maintain the representation of a stimulus long enough so that it can be recognized.

Each human physiological sense (sight, hear-ing, taste, smell, touch) is believed to have a corresponding store in sensory memory and three of these have been extensively studied: iconic memory, echoic memory, and haptic memory. *Iconic memory* stores visual representations for a very short period, typically half a second (e.g., the picture we just saw). People rely on visual representations to recall where they left their keys, for example. Visual representations are like pictures that can be mentally manipulated (Burton and Fogarty, 2003).

Echoic memory pertains to auditory stimuli, like the ability to comprehend and understand language (i.e., to keep sounds in our memory long enough to be able to make sense of them as words). Echoic memory hole information longer than iconic memory, generally for 1 or 2 seconds (Baddeley, 1997).

Haptic memory is used by the sense of touch. Sensory receptors all over the body detect sensations like pressure, itching, and pain, which are briefly held in haptic memory before vanishing or being transported to short-term memory. This type of memory seems to decay after about two seconds (Shih et al., 2009).

Sensory memory and attention cannot operate without each other. Memory has a limited capacity, and thus attention determines what will be encoded (Chun and Turk-Browne, 2007). Preserved information enters our brains via sensory receptors. They are stored in sensory memory just long enough to be transferred to short-term memory (Carlson et al., 1997). Although thousands of bits of information have been received through the five senses, the brain has to filter and select things to pay attention to. Attention is the process of consciously concentrating on one aspect of environment while preventing other things from being a distraction. This conscious perception is the first step of the memory process.

2.2.2 *Short-Term Memory*

Short-term memory (Atkinson and Shiffrin, 1968; James, 2007) is a limited-capacity system that receives information from sensory memory. Once the information has been received, only 7 ± 2 chunks (Cowan, 2001; Miller, 1956) of information can be held into short-term memory in consciousness, such as a phone number. Information is stored in short-term memory for a relatively brief duration, estimates range from 15 to 30 seconds without rehearsal (Sousa, 2016).

There are two major concepts for storing information in short-term memory: organization and repetition. A related issue to organization is the concept of chunking or grouping pieces of data. Chunking is a process by which individual pieces of information are bound together into a meaningful or familiar pattern. Chunking is also a type of elaboration that will help get information into long-term memory (Neath et al., 2003).

When information is placed in short-term memory, if it is actively repeated in mind, the incoming information can spend an extended period of time in short-term memory. The process of information repetition is called rehearsal. An example of this would be repeating the digits of a phone number until we dial them. This kind of mental repetition in order to maintain information in short-term memory is called maintenance rehearsal. Although this simple repetition does not appear to be very efficient at transferring information into permanent memory. Rather, deliberate efforts and elaborative rehearsal appears to be the most effective set of processes for the encode and transfer of information from short-term memory into long-term memory (Sousa, 2016; Willis,

2006) (I will discuss the long-term memory and elaborative rehearsal in the next section).

Relationship with working memory

Short-term memory is often used synonymously with working memory (e.g., in model human processor of Card et al.). However, an alternative model of human memory proposed by Baddeley (Baddeley, 1992) holds that there are two forms of memory distinct. It assumes that working memory allows for processing of information that can be used to solve problems, respond to environmental demands or achieve goals (Baddeley, 1992), whereas short-term memory is defined as the ability to store information temporarily (Brown et al., 2005; Klingberg, 2010).

According to this model, working memory includes both a storage capacity and a processing capacity. Processes such as rehearsal and reasoning are the work of a limited-capacity central executive system. The central executive is responsible for directing attention to relevant information, suppressing irrelevant information, and making decisions when two tasks are simultaneously performed. On the other hand, some studies suggest that working memory is not completely distinct from short-term memory (Cowan, 2008; Nadel and Hardt, 2011). But, some have suggested that both concepts represent the same cognitive process (e.g., (Nash, 2007)). Figure 6 illustrate several models to hypothesize the relation between short-term memory and working memory (Aben et al., 2012). In this chapter, short-term memory and working memory are considered the same entity.

The short-term and long-term memory distinction

In MHP, as represented in Figure 4 working memory is not completely distinct from long-term memory, since working memory consists of subset of activated chunks in the long-term memory (Card and Henderson Jr, 1986). In contrast, the modal model of Atkinson distinguished short-term from long-term memory. One of the most compelling pieces of evidence for this idea is the serial-position effect, Figure 7, which is the tendency to remember the items early in a list (i.e., the primacy effect) and later in a list (i.e., the recency effect) better than those in the middle (Henson, 1996). Primacy and recency effects are evidence that short-term and long-term memory rely on distinct systems. Recency effect arises because the last items are likely to be present in short-term memory, while primacy effect indicates that the first few items entered short-term memory and had time to be rehearsed and pass

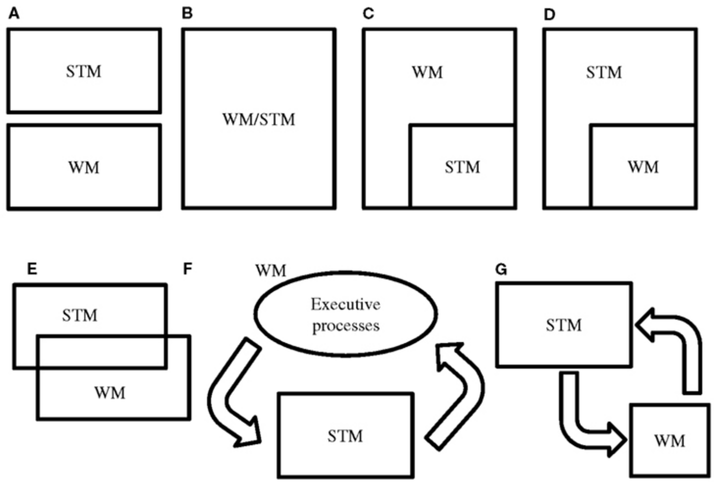

Figure 6: (Adapted from (Aben et al., 2012)) Hypothetical models of the relation between short-term memory (STM) and working memory (WM). (A) two independent, (B) identical entities.(C,D) STM is a part of WM and vice versa. (E) no transfer of information from STM to WM (or vice versa). (F) WM is STM plus additional processes. (G) information entering STM can be transferred to WM in order to undergo manipulation. (G) WM and STM as two different, but strongly collaborative entities.

on to long-term memory. The middle portion items probably can not be remembered because the increasing number of items fills the limited capacity of short-term memory and those items are unable to be properly transfer to the long-term memory. It shows that the items are recalled from two separate memory systems (Bjork and Bjork, 1996; Glanzer, 1972; Murdock Jr, 1962)

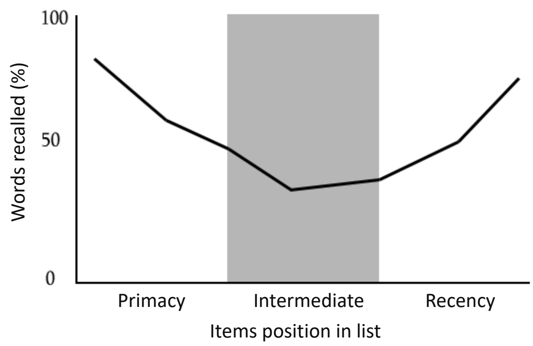

Figure 7: Serial position effect.

2.2.3 *Long-Term Memory*

Once the information has been encoded, the brain needs to retain the information over time and stores the encoded information in a permanent storage. Several types of information are represented in long-term memory, including such things as facts and events, motor and perceptual skills, knowledge of physical laws, a spatial model of the environment, attitudes and beliefs, etc (Hewett, 1999). Long-term memory has a large capacity for storage of information for long periods of time. Thus, information can be maintained in long-term memory from hours to days or months, or even a lifetime (Roberson and Sweatt, 1999; Shiffrin and Atkinson, 1969) (see Table 1 for more details).

There is, however, no easy or obvious way to determine the limits of how much can be stored, or for how long it can be stored. According to the modal model, the longer information remains in short-term memory, the more likely it is to make a permanent trace in long-term memory. Recovering information from long-term memory, known as retrieval, involves pulling information from the subconscious long-term memory and making it immediately accessible to the conscious mind (i.e., bringing information back into short-term memory).

2.2.3.1 *Varieties of long-term memory*

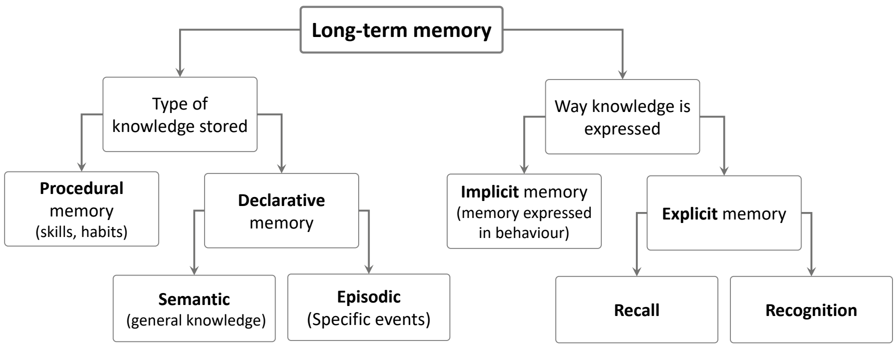

Figure 8: (Adapted from (Burton et al., 2014)) model of the different types of long-term memory.

Types of long-term memory can be distinguished by kind of stored knowledge and the way this knowledge is retrieved and expressed. In general, two kinds of information are stored in memory: *declarative* and *procedural* memories. Declarative memory refers to memory for facts and events, that are explicitly stored and consciously 'declared' (Squire, 1986). Calling up a memory from the past, requires access to declarative memory. Declarative memory can be *semantic* or *episodic* (Tulving, 1987; Tulving et al., 1972). Semantic memory refers to general world knowledge or facts (Tulving et al., 1972). Episodic memory consists of memories of particular events, rather than general knowledge (Tulving, 2002). Episodic memory allows people to remember thoughts and feelings from the recent or distant past, or to imagine the future (Wheeler et al., 1997)

Procedural memory refers to 'how to' knowledge of procedures, skills or habit. Although procedural memories often form without conscious effort (how to ride a bike), at other times procedural memories are residues of prior conscious knowledge and strategies, which have become automatic and highly efficient.

For example, when we learn to type, we study the layout of the keyboard, tapped out the letter one-by-one using hunt-and-peck[3] (Figure 9). In this stage, we are trying to form declarative memories. As we are typing our first words, we also hold in short-term memory (or working memory) the sequence of keys to hit and knowledge about which fingers to use for each key. Over time, however, our speed and accuracy improve, while conscious effort diminishes. Practice allows to build up memory of keys, therefore specific letters can be accessed without thinking about key locations (Goldberg and Richardson, 1993). This process reflects the formation of procedural memory for typing. In the end, we think only of the words we want to type without looking at the keyboard layout [4] and would have difficulty describing the layout of the keyboard (declarative memory), even though our fingers 'remember', Figure 9.

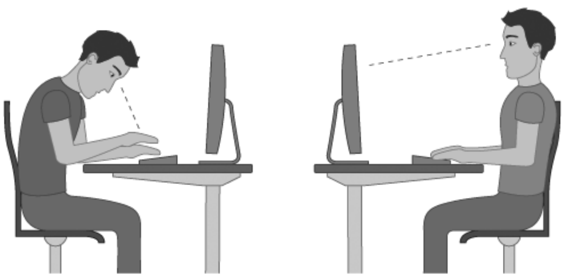

Figure 9: Left, hunt-and-peck method (declarative memories); Right, touch-typing (procedural memory).

Knowledge can be retrieved *explicitly* or *implicitly* (Schacter and Buckner, 1998). Explicit memory refers to the conscious retrieval of information, whereas implicit memory refers to memory that is evident in skills, conditioned learning, associative memory and behaviour. Some psychologists use explicit and implicit memory

[3]Hunt-and-peck is a method of typing in which one looks at the keyboard and types using usually the index fingers.

[4]Touch-typing is typing in a chains of anticipated motor actions that are executed semi-autonomously. It enables "eyes-free" operation in which the typist keeps their eyes on the source copy at all times (Uddin et al., 2017).

as synonyms for declarative and procedural memory. Although there is clearly some overlap, the declarative-procedural refers more to the type of knowledge that is stored, whereas the explicit–implicit distinction refers more to the way this knowledge is retrieved and expressed. There are two kinds of explicit retrieval: recall is the spontaneous conscious retrieval of information from long-term memory, as when a person brings to mind the name of a country (Anderson and Bower, 1972; Henderson, 1999). Recognition is memory for whether something currently perceived has been previously encountered or learned (Burton et al., 2014). Figure 8 provides different types of long-term memory.

2.2.3.2 *Encoding and organisation*

After discussing the varieties of long-term memory, it is worth considering how does information find its way into long-term memory at first? How is information organised in the mind to be retrieved? For information to be retrievable from memory, it must be encoded. *Encoding* refers to any mental operations performed on information to cast into a representational form, or 'code' that can be readily accessed. How to pay attention and how to encode the information has a substantial influence on its accessibility. The evidence suggests that memory retrieval is an almost automatic process. Thus, distraction at the encoding time, can extremely reduce retrieval success (Healey and Miyake, 2009).

Some encoding is deliberate, such as studying for an exam. However, much of the time encoding simply occurs as a by-product of thought, perception or emotional arousal. For example many people can recall precisely where and when they first heard the news of the September 11 attacks on the United States in 2001. This is called Flashbulb memories, which is the vivid memories of exciting or highly consequential events (Neisser and Winograd, 1993).

As noted earlier, the simple repetitive rehearsal that maintains information temporary is not optimal for long-term memory. Thus, elaboration on rehearsal seems to be one of the most effective strategies to get information into long-term memory. Elaborative rehearsal goes beyond simple repetition. It is the process of linking new information to pre-existing knowledge stored in memory and looking for relationships between information. Elaborative rehearsal of a telephone number may involve looking for patterns or associations. This approach requires the learner to engage with new information in a way that creates meaningful connections to previously-learned things. One explanation (Anderson and Reder, 1979) suggests that the memory traces that elaborate

Feature	**Sensory memory**	**Short-term memory**	**Long-term memory**
Entry of information	Preattentive	Requires attention	Rehearsal
Maintenance of information	Not possible	- Continued attention - Rehearsal	- Repetition - Organization
Format of information	Literal copy of input	- Phonemic - Probably visual - Possibly semantic	- Largely semantic - Some auditory and visual
Capacity	Large	Small	No known limit
Information loss	Decay	- Displacement - Possibly decay	- Possibly no loss - Loss of accessibility or discriminability by interference
Trace duration	0.25-2 Seconds	Up to 30 seconds	Minutes to years
Retrieval	Readout	- Probably automatic - Items in consciousness - Temporal cues	- Retrieval cues - Possibly search process

Table 1: Commonly accepted differences between memory systems (Craik and Lockhart, 1972).

the previously stored information provide additional routes to new information.

Information that is encoded on a deeper level, through meaningful association, is easier to remember. The degree to which information is elaborated and processed during encoding is referred to *level of processing* (Craik and Lockhart, 1972; Lockhart and Craik, 1990). Information can be processed to different depths:

- Shallow or structural level: focusing on physical characteristics of the stimulus
- Phonemic level or intermediate level: focusing on simple characteristics of stimulus
- Semantic level: focusing on the meaning of the stimulus

Aside from the level of processing, two other variables influence accessibility of memory, the spacing effect and the use of multiple representational modes. The spacing effect refers to distributed learning over time rather than massed together within a shorter period. Studies on spacing rehearsal (Bahrick et al., 1993; Callan and Schweighofer, 2010) demonstrate that spacing sessions over longer intervals tends to double long-term retention of information. Spacing the rehearsal of information provides time for memory to consolidate some information before encoding new information. Consolidation is a time-dependent process occurring after encoding, presumably by structural and chemical changes in trace memories. In this process a temporary, unstable memory is transformed into a more stable, long-lasting form during intervals (Squire et al., 2015). Experts emphasize on sleep's critical role in the consolidation process (Rasch and Born, 2013).

Encoding the information in multiple representational modes such as words, images and sounds, increases the ability to retrieve information from long-term memory (Paivio, 1991). For instance, many people remember the passwords not only by memorising the digits but also by forming a mental map of the buttons they need to push and a motor control (procedural) representation of the pattern of buttons to push that becomes automatic and is expressed implicitly.

Important information needs to be organized based on meaning or semantic codes to be gradually transferred into long-term memory (e.g., learning the country's names on the same continent) (Sousa, 2016). In this case, information is stored in networks of association and each piece of information within the network is called a node. Nodes may be thoughts, images, concepts or any other piece of information. That one node may have connections to many other nodes leads to networks of association. Activating one node in a network triggers activation in closely related nodes. Memory research (Bradshaw and Anderson, 1982; Budiu et al., 2009) has shown that, when people are provided with additional information that is highly semantically related to the content they are learning, they typically show better memorisation as compared to the random content.

2.3 FORGETTING

Forgetting is the opposite of remembering. Forgetting is the temporary or permanent failure to retrieve information already stored in memory (Fleming, 2019). According to the Ebbinghaus's study (Ebbinghaus, 1964), forgetting follows a standard pattern that occurs with many kinds of declarative knowledge. It happens with rapid initial loss of information after learning and only gradual decline thereafter. As shown in Figure 10, increasing initial study time (the dotted line) increases retention, but forgetting occurs at the same rate.

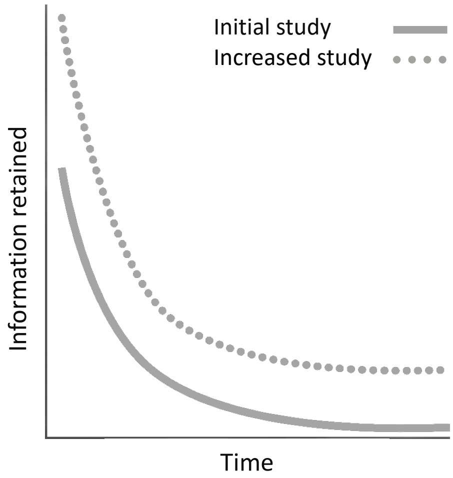

Figure 10: (Adapted from (Burton et al., 2014)) Rate of forgetting.

Forgetting may occur in relation to both short- and long-term memory. Forgetting from short-term memory is usually explained in terms of the information simply being lost due to its limited-capacity (Murdock Jr, 1962) and limited-duration (Brown, 1958). But what about forgetting from long-term memory? Psychologists often distinguish between the unavailability of information in long-term memory or its inaccessibility (the ease with which it can be retrieved) as forgetting. The tip-of-the-tongue phenomenon is a good example of information that is available but inaccessible. People sometimes experience this phenomenon in which the person knows the information is 'in there' but is not quite able to retrieve it (Brown and McNeill, 1966). Another example is that people learn seemingly forgotten information much more rapidly the second time it is presented as compared to the first time. In other words, relearning is faster than initial learning, since the information is still available in memory (Miendlarzewska et al., 2018; Sadeh et al., 2014). But if the information is available, why do people sometimes forget things entirely? Psychologists have proposed several explanations, including *decay*, *retrieval failure* and *interference* (Fleming, 2019; McLeod, 2007).

2.3.1 *Decay theory*

Decay theory explains forgetting as a result of a fading memory trace over time. When new information is learned, it leaves a trace in the brain. Under this theory, to retrieve a memory, a certain pathway or trace needs to be followed to the place where it is stored. These traces fade with disuse over time (Brown, 1958; Peterson and Peterson, 1959; Ricker et al., 2016). Disuse of information leads to a gradual decrease in the strength of memory traces, which will ultimately cause retrieval failure. Thus, even though the information remains in memory, it is inaccessible.

2.3.2 *Retrieval failure*

Retrieval failure is caused by encoding failures and lack of retrieval cues. A common reason why we don't remember information is because a memory was never encoded and formed into long-term memory in the first place (Coon and Mitterer, 2012; Kirchhoff, 2009; Nickerson and Adams, 1979). Moreover, retrieval fails due to the absence of memory cues (Eysenck, 2001; Tulving, 1974). In other words, the information is available, but since the retrieval cues are not associated with that piece of information, it is not accessible. More elaborately encoded memories can effectively improve memory, enhance retention of information and help prevent retrieval failure (Jerabek and Standing, 1992).

2.3.3 *Interference theory*

One of the prime cause of memory failure is interference (Radvansky et al., 2011), the intrusion of similar memories on each other (Eysenck, 2001). For example, when people confuse typing with two similar keyboard layouts (e.g., French and English). In this example on the French layout, key A (i.e., stimulus) is in the location of (1,1) (i.e., response), but on the English layout it locates in (2,1). The theory states that the occurrence of interference is maximal when two different responses have been associated with the same stimuli. The interference is intermediate when the same stimulus is associated with two similar responses, and minimal when there are two different stimuli (Osgood, 1949; Underwood and Postman, 1960). One explanation for this phenomenon is retrieval competition (Dudai, 2004; Wixted, 2004). If a retrieval stimulus elicits multiple memories, there will be a competition between a new association to that stimulus with an older association to determine which will be recalled (e.g., key A has been associated with two locations). The new association prevents the older one from being remembered.

There are two ways in which interference in long-term memory can cause forgetting. When new memories tend to impair retrieval of existing memories, there is a *retroactive* interference, and when old memories alters new memories, there is *proactive* interference. I will discuss both proactive and retroactive interference in detail further on Chapter 4.

Decay and interference: similarities and differences
Both decay and interference may cause forgetting which is the loss of stored (old) memories with the passage of time. Memory traces fade over time in decay theory. In interference theory, memories are lost when new memories are created.

Decay and interference theory differ in that interference occurs when new information interfere with the ability to recall old information, however decay is caused by disuse over time. Decay theory is a passive method of forgetting as no interference is produced. Interference theory is an active process because the act of learning new information directly prevent the recollection of previously learned information (Fleming, 2019).

2.4 CONCLUSION

The focus of this thesis is the interference of previously learned information with learning new information while alternating between interfaces. Although a detailed discussion of this topic is left for later in Chapter 4, the present chapter provided an overview of various phenomena related to memory process of learning and forgetting from cognitive psychology literature. I believe that these topics are critical to our understanding of how interference occurs in the memory when we alternate between different interfaces.

Therefore, this chapter began with describing memory and outlined the model of information processing. The standard model of memory is predicated on the metaphor of the mind as a computer and distinguishes three memory systems: sensory memory, short-term memory and long-term memory. Making a memory is a multi-step process that includes encoding, storing, and retrieving information in these memory systems. Encoding is the act of getting information into the memory system processing (sensory memory). Storage is retention of the information (long-term memory), and retrieval is the act of getting information out of storage and into conscious awareness (short-term memory).

The major types of long-term memory were also identified and thoroughly discussed in this chapter. Types of long-term memory can be distinguished by the kind of knowledge stored and the way this knowledge is retrieved. Two kinds of information, declarative and procedural can be stored in the long-term memory. Declarative memory refers to memory for facts and events and is subdivided into semantic: general world knowledge and episodic memory: memories of particular events. Procedural memory refers to 'how to' knowledge of procedures or skills. Moreover, it explained that Information can be retrieved either explicitly or implicitly. After introducing the varieties of long-term memory, I discussed how information can be encoded and organised in long-term memory, such as the spacing of practice, elaboration practice, as well as encoding the information in multiple representational modes.

Finally, I explored different types of forgetting. One possibility in short-term memory is that memories simply decay in passage of time. Forgetting occurs in long-term memory due to decay, retrieval failure, and interference. Interference is the main reason of forgetting memory. The next chapter gives an overview of learning and skill acquisition.

3 SKILL ACQUISITION

This chapter provides definitions, factors, theories and models related to the skill acquisition from cognitive psychology literature. First discussed is the most widely accepted model of learning; the three-stage model proposed by Fitts and Posner. Then, this chapter explains the basic laws and fundamental principles of learning, such as performance, power law of Practice and the asymptotic nature of learning. At the end, it presents different interaction techniques to improve user performance on text entry tasks. In the next chapter, another fundamental principles of learning, the transfer of skill, will be discussed.

3.1 DEFINITIONS

In this section, I provide the definitions related to the skill acquisition.

3.1.1 *Skill*

A skill, such as typing, playing the piano, or driving, is a learned and goal-directed activity that entails a broad range of human behaviors (Edwards, 2010). Everyone has learned a new skill. Learning (as discussed in Chapter 2) is the process by which people acquire the capacity to perform a new skill. Generally, learning a skill requires practice. With enough practice, task performance improves, and may become automatic, with little or no need of attention. Touch-typing is an example of a highly practiced skill.

3.1.1.1 *Skill domains*

A skill domain is a classification system for similar skills based on the essential capacities for successfully accomplishing them. A skill belongs to one of three domains: cognitive, perceptual, or motor. In a *cognitive skill*, successfully accomplishing the skill is primarily determined by person's knowledge and cognitive abilities (e.g., reading, writing, memorizing a list of words and computer programming). *Perceptual skill* is the ability to recognize important information among sensory stimuli in the environment (e.g., adjusting the color on a monitor set and sorting things by size). *Motor skill* is movement through muscular contributions (e.g., typing and playing football) but are not performed in isolation from perceptual and cognitive skills. Where cognitive skills emphasize knowing what to do, and perceptual skills getting the information to do it, motor skills are concerned with doing it correctly (Edwards, 2010).

3.1.1.2 *Skill components*

There are three components influencing the performance of motor skills (Figure 11). According to the Newell's Model (Newell, 1986), these components include the *person* performing the skill (who), the *task* that is performed (what), and the *environment* in which the skill is performed (where). All components must be taken into account for the fullest understanding of skill.

Each individual *person* brings a unique composition of structural and functional characteristics: structural such as height, weight, and body type, and functional characteristics including cognitive, motivational, emotional, and other psychological attributes. In addition, factors such as previous experiences (i.e., novice (Dix et al., 2003; Nielsen, 1994) or expert (Butler, 1985)) are included in this component. These features play a significant role in performance of skill.

The second component influencing skill performance is the *environment* in which a person executes the skill. Skills may be performed within environments that are predictable or unpredictable, similar or dissimilar to practice conditions, recreational or competitive. For example, one can practice typing with a QWERTY keyboard layout, but at workplace there exists only DVORAK keyboard layout. Skills may also be performed alone or in the presence of others. Physical conditions of the performance context may also influence performance characteristics. Lighting conditions, temperature and humidity significantly alter the performance of many skills.

The nature of the *task* is the third influential component that includes: the goal of the task, the rules, and the tools used in performing the task. For example, considering typing as a task, the goal is to write down the words, with minimum error (rule) and using a keyboard layout (tool).

3.1.2 *Skill acquisition*

Skill acquisition is described as the internal processes that bring relatively permanent changes in the learner's capabilities (Schmidt and Wrisberg, 2008). For example, a skill such as riding a bicycle requires a good deal of practice for the learner to perform

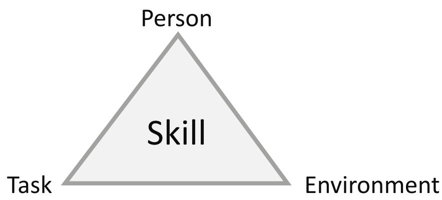

Figure 11: Three components influencing skill performance.

it successfully. In order to acquire a skill, learner needs to interact effectively with the environment, detect important information and time to response appropriately. It should result in coordination patterns that are adaptable to a range of varying performance characteristics. Adaptive behavior is important because conditions like the environment, task requirements, and motivations can change the skill performance (Davids et al., 2006). One way researchers have tried to understand skill acquisition is by examining performance changes over time (Davids et al., 2008).

3.1.3 *Performance*

Performance (Edwards, 2010) is qualitative or quantitative assessment of what can be observed during the execution of a skill at a specific time and in a specific location or situation. Performance could have a wide range of definitions, such as completion times, error rates, or percentage of functionality understood (Grossman et al., 2009). In this thesis, I consider performance as selection times.

3.1.4 *ART measures*

There are three measurements of performance that generally are assessed to accurately determine the degree of learning (Edwards, 2010). These measures contribute to our understanding of the learning process:

Acquisition measurements refer to the direct measurement of performance observed over time. It determines the rate of learning. A series of acquisition measures may be graphed to illustrate changes in performance over the course of practice and is referred to as a performance curve.

Retention tests refer to performance measurements conducted subsequent to acquisition observations. They provide sufficient time to allow any effects of performance variables to dissipate. Retention refers to the persistence of original learning over a period of no practice.

Transfer tests measures how effectively a person can transfer the learning of a skill from one condition to another. (Transfer of skill will be discussed in greater detail in Chapter 4)

ART measures is an acronym for these three types of measurements.

3.1.5 *Intramodal improvement*

Intramodal improvement (Cockburn et al., 2014) refers to the magnitude of skill performance improvement through practice with a certain method and task. As illustrated in Figure 14, improvement in performance continues as long as practice continues, but the amount of improvement gradually and predictably diminishes over time.

3.2 THEORIES

When learning skills, there are distinct behavioral stages that learners experience. These stages may be experienced at different rates, but passage through each stage seems essential for the learners. Several theories[1] and models have been proposed for identifying these stages (Adams, 1971; Anderson, 1982; Cockburn et al., 2014; Fitts and Posner, 1967; Gentile, 1987; Newell and Van Emmerik, 1989; Rasmussen, 1986; Vereijken et al., 1992).

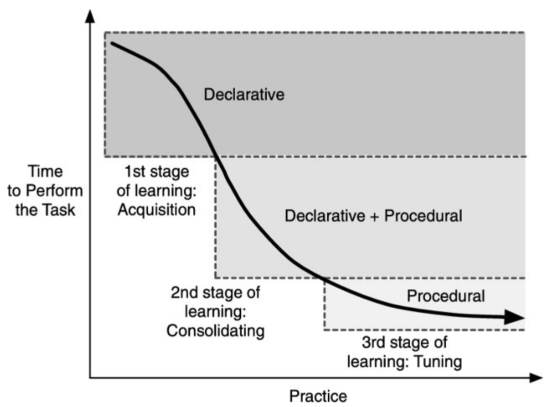

Figure 12: Theory of learning in the three stages. Adapted from (Kim et al., 2013).

[1] A scientific theory is a statement or set of statements that relates a large number of observations into a logical and testable framework (Edwards, 2010)

3.2.1 *Fitts three-stage model*

In 1967, two psychologists, Paul Fitts and Michael Posner, proposed a three-stage model of motor skill learning that became the most widely accepted and used in fields concerned with the learning and motor skills. Based on observations that different cognitive, perceptual, and motor abilities are involved at different points in the learning process, they proposed three learning stages: cognitive, associative and autonomous (Fitts and Posner, 1967). The model represents a cognitive theoretical approach to classifying learning stages, with the progression from declarative to procedural memory to explain changes in behaviors in each stage. As shown in Figure 12, it is based on acquiring declarative and procedural knowledge at first stage, consolidating the acquired knowledge at the second stage, and finally with sufficient practice, converts the acquired knowledge into procedural at the third stage (Kim et al., 2013).

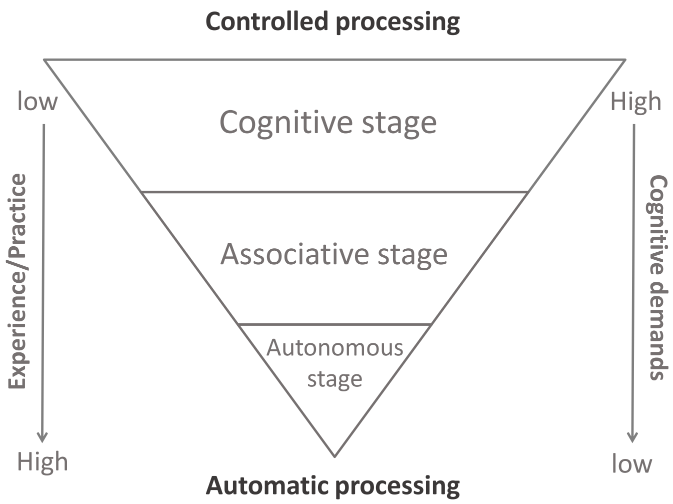

Figure 13: Fitts and Posner's model of skill acquisition (Fitts and Posner, 1967) as a function of the cognitive demands placed on the learner and his level of experience.

3.2.1.1 *Cognitive stage*

The cognitive stage is the initial stage of skill acquisition. during this stage users are learning and understanding what to do. The learners have to be intellectually aware of the task in the context of understanding task instructions, general conceptualization with task goals, developing strategies for task accomplishment and determining how a task should be evaluated. These efforts require a high degree of cognitive activity including attention. The cognitive stage is also characterized by frequent errors, awkwardness, and some disorientation. Thus, learners require continuous feedback or information on their progress.

Once the learners have acquired the basic procedures, they proceed to the associative stage of skill acquisition. To go beyond this stage, the learners need to experiment with a variety of strategies, abandoning those that do not work and developing consistent strategies. Thus, the improvements in performance are quite large in this stage, as a result of selecting the most effective strategy for the task.

3.2.1.2 *Associative stage*

After the cognitive stage, learners enter the associative stage and begin to develop associations between specific stimuli and suitable action responses. During this stage users are learning how to do the task. By this time, the learners have selected the best strategy for the task to refine the skill and make performance quicker and less error-prone.

This stage is the largest and longest stage and may last for days and months, depending on the intensity of practice. Performance improvement occurs more slowly, as the learners focus more on refining a particular pattern rather than selecting among alternative strategies (Schmidt and Lee, 1988).

3.2.1.3 *Autonomous stage*

When learners can perform consistently, often with little or no attentional effort, they are said to have reached the autonomous stage. During this stage cognitive processes are low or automatic. The main characteristics of the autonomous stage are the opposite of the consciously controlled cognitive stage. Performance at this stage of skill acquisition is very quick and very accurate (Ackerman, 1992). In this stage, the learners can devote their attentions to the other aspects of the skill or focus on a secondary task. Most learners move from stage to stage as they learn skills. However, some might not move on to the last stage, due to the training demands, the complexity of the task or a lack of motivation.

3.2.2 *Other theories*

Other theories influenced by Fitts and Posner, such as theory of cognitive skill acquisition (ACT-R) by Anderson (Anderson, 1982) comprises three stages: declarative, transitional and procedural. Rasmussen (Rasmussen, 1986) proposed learning stages as knowl-

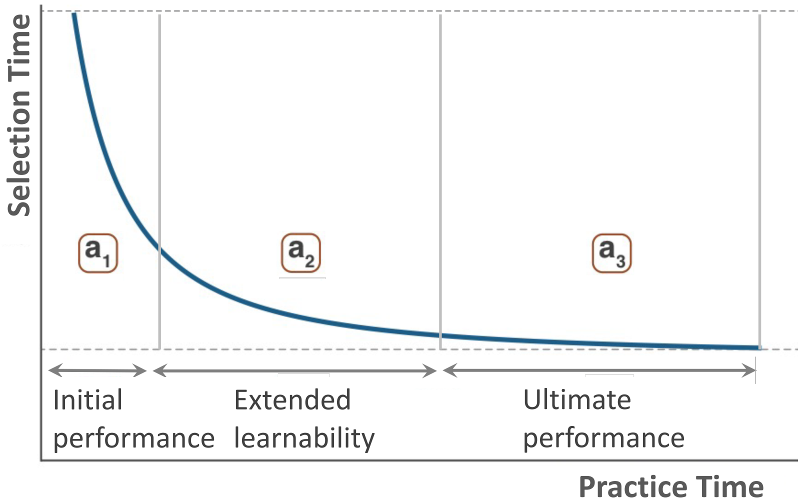

Figure 14: Adapted from (Cockburn et al., 2014). Conceptual model of intramodal power law of learning performance over time for one one particular interface. (a_1) initial performance, (a_2) extended learnability, (a_3) ultimate performance

edge based, rule-based and skill-based. VanLehn (VanLehn, 1996) also described three stages of skill learning: early, intermediate and late. Cockburn (Cockburn et al., 2014) subdivided intramodel improvement into three stages (Figure 14) as initial performance (i.e., initial performance with the task), extended learnability (i.e., change in performance over time), and ultimate performance (i.e., maximum level of performance) which are suggestive of Fitts's model. Therefor, initial skill is processed through cognitive stage, followed by forming the conceptual associations, that result in the autonomous skills development. In overall, it appears that (1) All of these theories have three stages and they (2) share a high degree of similarity.

3.3 FACTORS

This section discusses a number of factors responsible for the development of skills.

3.3.1 *practice*

Practice is the single most critical factor in the learning of skills. Although almost any practice improves the performance of skills, the way in which it is organized plays an important role in the stability and amount of learning that results. For example, interskill practice can promote better practice performance levels. *Interskill* practice is the scheduling of different skills within a practice session. Interskill practice can be arranged into two ways: *blocked* *practice* (i.e., the same skill is rehearsed in repetitive way) and *random practice* (i.e., different skills are rehearsed in an unpredictable order) (Edwards, 2010). For example, if three skills labeled A, B, and C are presented during a practice period, a blocked practice is as follow: AAA... BBB... CCC.... In random practice, the same number of practice trials for each skill may be completed, but the trials are presented in random order: BCACBBACBCAA.... In scheduling interskill practice sessions, blocked practice promotes better practice performance levels, although random practice often results in superior levels of learning.

3.3.2 *Distribution of practice*

After deciding the ordering of skills in a practice, the next important factor to be considered is the distribution or spacing of practice (Carpenter et al., 2012; Cepeda et al., 2006). The balancing of periods of rest and work within a practice session can influence the learning of skills. Rest periods between sessions improve performance, and longer rest periods being more beneficial than short ones. Distribution of practice is specified as being either massed or distributed. *distributed* practice involves longer periods of rest and shorter periods of work, and *massed* practice involves less time in rest and longer periods work. This distribution can apply across several practice sessions or within a single session. Research (Cepeda et al., 2006) shows that distributed practice has far more impact on performance than massed practice.

3.3.3 *Deliberate practice*

In addition to the amount and distribution of practice, the quality of that practice is critical to skill learning (Ericsson et al., 1993, 2006). Deliberate practice is a effortful, highly structured and organized form of practice. It generates no immediate rewards, and is motivated by the goal of performance improvement rather than enjoyment. Consequently, when engaging in sufficient deliberate practice, learners attain expertise in a skill (Anders Ericsson, 2008).

Deliberate practicing can distinguish an expert from somebody who is highly skilled in everyday activities. The goal for everyday activities is to quickly reach an acceptable level of mastery that is stable and autonomous and then executed with a minimal amount of effort (see Figure 15). In contrast, the expert performance continues to improve as a function of deliberate practice. Expert performers remain within the cognitive/associative stages to attain higher levels of control of their performance, thus counteract automaticity. At some point, the experts stop engaging in deliberate practice and focus only on maintaining their performance, which results in premature automation (arrested development) (Starkes and Ericsson, 2003).

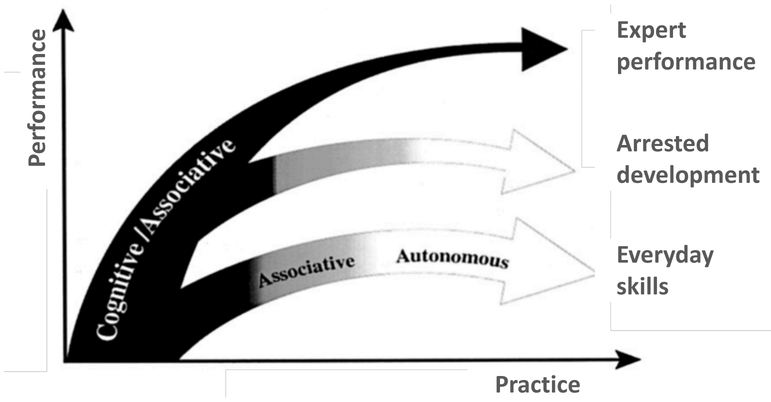

Figure 15: An illustration of the difference between the improvement of expert performance and everyday activities. Adapted from (Ericsson, 1998).

3.3.4 *Decay*

The next important factor relates to the learning of skill is decay (discussed in Chapter 2). As the time between instances of exposure increases, the memory starts to decay and performance gets worse.

3.4 MODELS

In this section, I discuss the computational models related to the main factors of skill acquisitions such as practice (i.e., number of repetition), spacing effect and decay (i.e., time since last presentation).

3.4.1 *Power law of practice*

Improvement in performance continues as long as practice continues, but the rate at which it occurs gradually and predictably diminishes over time. It can be expressed mathematically as a power function and in the form of learning curves. Accordingly, intramodal improvement is well characterized by the equation of the "**p**ower **l**aw of **p**ractice (PLP)". The law of practice is one of the most ubiquitous and highly reliable laws in learning theory

(Anderson, 1982; Newell and Rosenbloom, 1981; Roessingh and Hilburn, 2000).

$$T_X = a.X^{-b} + c \tag{1}$$

where T_X is task completion time, that allows us to estimate temporal performance of a task in the future practice (Wobbrock, 2007).

X is the amount of practice time.
a is the amount to be learned
b is the learning rate (i.e. the curve steepness).
c is the asymptotic selection time (Figure 14a_3).

A main conclusion of this law is that as long as practice continues, learning never really stops which is known as the *monotonic benefits assumption*. Furthermore, the law of practice expresses that there exists some upper limit to learning that is progressively approached with practice but that is never reached and is called an *asymptotic nature of learning*.

3.4.2 *Predictive performance equation*

Predictive **p**erformance **e**quation (PPE) (Walsh et al., 2018) is a computational model of learning and retention that makes performance predictions at the user level based on (1) prior performance and (2) the learning schedule of a user. It attempts to account for three factors of learning: amount of practice, decay, and distributed practice.

PPE is composed of five equations. In PPE, the effects of practice and temporal decay on *activation* M of item n are multiplicative (Equation 2). Practice as the first factor is used in the equation of power law of practice (Equation 2, T_x). In PLP, as stated above (Section 3.4.1), performance improves with increasing the number of exposures to a task (X). The second factor is the power law of decay (Equation 2, T^{-d}):

$$M_n = T_X * T^{-d} \qquad (T_X = a.X^b + c) \tag{2}$$

X is the number of practice repetitions, T is temporal decay in seconds, a is the amount to be learned, b is the learning rate, c is the asymptotic selection time and d is the decay rate.

In PPE, temporal decay is calculated as the weighted sum of the time since each of the previous practice events(Equation 3):

$$T_n = \sum_{i=1}^{n-1} w_i.t_i \tag{3}$$

The weight assigned to each event decreases with time (Equation 4):

$$w_i = t_i^{-x} \sum_{j=1}^{n-1} \frac{1}{t_j^{-x}} \tag{4}$$

where the variable x controls the steepness of weighting, wherein higher values result in larger weights for the more recent practice events.

The third factor is temporal distribution of practice over time or spacing effect, which is represented within the decay parameter, d (Equation 5).

$$d_n = f + m.\left(\frac{1}{n-1} \sum_{j=1}^{n-1} \frac{1}{\ln\left(lag_j + e\right)}\right) \tag{5}$$

Spacing used two parameters f (decay intercept parameter), and m (decay slope parameter), and also cumulative average lag time between trail. As practice sessions occur together (i.e., massed), the decay increases. As practice becomes distributed (i.e., spaced), the decay decreases. Finally, activation (M_n) is placed within a logistic function and adjusted according to a threshold parameter (Equation 6).

$$Performance_n = \frac{1}{1 + \exp\frac{\tau - M_n}{s}} \tag{6}$$

where the parameters τ and s control the slope and intercept of the logistic function. Small value of s increase sensitivity of performance to changes in activation. Small or negative values of τ, in turn, increase the overall level of performance

PPE model assumes that performance follows a continuous performance curve which derive from evaluation aggregate learning curves which is not inline with skill acquisition literature. It shows that users have gone through discrete learning phases. Thus, Collins et al. (Collins et al., 2020) proposed TAPPED model to refine previous PPE model.

3.5 INTERACTION

In the previous sections, I discussed the foundations of skill acquisition in cognitive science. In this section I discuss how these finding are used in HCI and more precisely in text entry.

3.5.1 *Use-case: text input*

I focus on text input as it is one of the most common task in HCI with several contributions in term of interaction techniques (Kristensson and Zhai, 2007; Shi et al., 2018; Zhai and Kristensson, 2003), empirical studies (Clarkson et al., 2005; MacKenzie and Zhang, 2001), models of performance (Jokinen et al., 2017; Kieras and Bovair, 1986a) as well as optimization methods (Bi and Zhai, 2016; Bi et al., 2010; Dunlop and Levine, 2012). Text input including writing emails and messages, writing articles, filling forms, typing commands, and coding, is used in everyday tasks through textual interfaces. An efficient textual interface should be learned with a low initial learnability and sufficient amount of practice. Therefore, an average user should be able to type with a sufficient speed without many errors (Zhai et al., 2005).

There are various layouts such as QWERTY layout for English, AZERTY layout for French, QWERTZ layout for German. Such layouts can be used with different keyboards such as physical and virtual keyboard.

Physical keyboard are available in different sizes: desktop-size, laptop-size or thumb-sized[2]. Virtual keyboards are on-screen keyboard with active graphical keys that allows to input the characters mostly via a touchscreen interface.

In addition, Dvorak is an optimized layout designed to be easier to learn, more accurate, faster, and less fatiguing than the Qwerty (MacKenzie and Tanaka-Ishii, 2010). Based on a study where participants already learned the QWERTY layout (Lessley, 1978), participants were about 17% faster with the DVORAK layout.

In the rest of this thesis, the term *method* refers to the keyboard layouts and interaction techniques to input text. *Keyboard layout* refers to both the arrangement of the keys (i.e. position and size) as well as the mapping between keys and characters. *Interaction techniques* refer to the interaction sequence to select characters.

In the next section, I will discus different interaction techniques for text input that have been proposed to improve skill acquisition in different stages of learning.

3.5.2 *Interaction technique*

At the first stage of learning, when users encounter a new interface, for example a new keyboard layout, they search visually and rely on their prior experiences to find the new key locations. Two

[2]Thumb-sized keyboard is a small external keyboards used for devices without a built-in keyboard, such as PDAs, and smartphones

user studies (MacKenzie and Zhang, 1999; Smith and Zhai, 2001) indicate that the initial typing speed is moderate (around 10–15 words per minute) for novice users when the layout is new or unfamiliar to them. MacKenzie and Zhang (MacKenzie and Zhang, 1999) compared their new design OPTI (MacKenzie and Zhang, 1999) with a QWERTY layout in a 20 sessions of text entry. Average entry rates for OPTI layout was weak at first, 17.0 wpm and increased to 44.3 wpm at session 20. The average entry rates for participants having prior experience with QWERTY were 28 wpm initially (Figure 16).

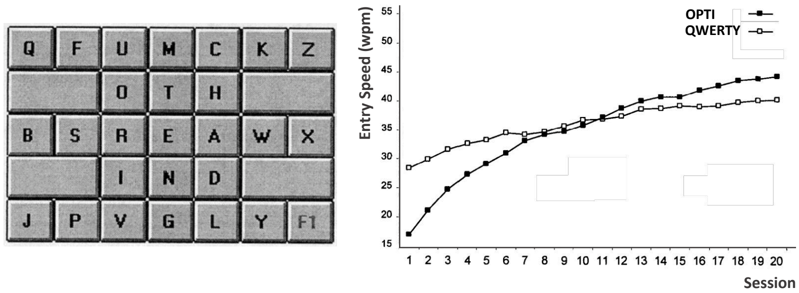

Figure 16: Adapted from (MacKenzie and Zhang, 1999). Left, The OPTI soft keyboard layout, in which 10 most frequent letters were placed in the center of the keyboard. The 10 most frequent digraphs were assigned to the top 10 keys, then the remaining letters were placed. Right, Entry speed by keyboard layout and session.

To reduce the impact of visual search on the performance of novice users, Smith and Zhai (Smith and Zhai, 2001) introduced an alphabetical ordering layout. They conducted a study to test whether alphabetical ordering could offer the advantage in the initial stage of learning a new layout. Results show that participants' average speed was 9% faster with a new alphabetically tuned keyboard.

With this layout, users with no prior experience could reduce their visual search time. Because the area that a letter is located, can be easily anticipated comparing to the location of the other letters. Particularly in the case that letters are at the beginning or the end of the alphabet, novice users type faster, see Figure 17.

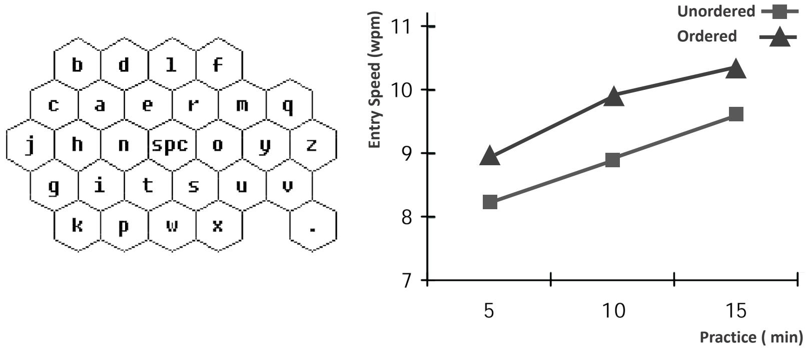

Figure 17: Adapted from (Smith and Zhai, 2001). Left, an alphabetical ordering keyboard layout. Right, participants' typing speed, with and without alphabetical order.

After first stage (i.e., initial learning) and during training, practice and effort, as well as interfaces' feedback, allow users to attain a maximal level of performance (Nielsen, 1994). The required time to reach a specified level of proficiency in initial stage of learning can be easily measured, as only the users with no prior experience with that method are needed. However, it is not obvious when the first stage stops and the next stage starts. Moreover, the measurement of second stage can last over a long period of time (months to years) to accurately evaluate the next stages (Nielsen, 1994).

At the third stage (i.e., ultimate performance), users reach an asymptote, which is a high level of expertise given a certain method (e.g., a keyboard layout) and task (e.g., text input). This stage indicates the potential benefits of a method after enough practice. For instance, the DVORAK keyboard has shown highest ultimate performance to QWERTY by 4-5% (Buzing, 2003; West et al., 1998).

However, ultimate performance does not inform how quickly users learn the method. According to Cooper's study (Cooper, 1983), typists need more than 100 hours of practice on Dvorak keyboard to surpass their old QWERTY performance. Therefor, the process of assessing ultimate performance of a new keyboard can be costly, especially if many participants are employed (Zhai et al., 2005).

The learning curve has been observed in many text editing techniques (Card, 1983; Kristensson and Zhai, 2007; MacKenzie and Zhang, 1999; Oney et al., 2013; Shi et al., 2018; Zhai and Kristensson, 2003; Zhai et al., 2002; Zhu et al., 2018). For instance, Shi et al. compared the method GestAKey (Shi et al., 2018) with two regular methods (hotkey and long press) and show that users reach ultimate performance faster with the GestAKey. MacKenzie et al (MacKenzie and Zhang, 1999) used the PLP model to predict the upper-bound text entry rate for soft keyboards, and then designed a new keyboard layout "OPTI" with a predicted upper-bound entry rate of 35% faster than the predicted rate for a QWERTY layout.

PLP also has been used to predict the novice users' learning rate (i.e. words per minute rates) on the Twiddler, a mobile one–handed chording keyboard (Lyons et al., 2004). Isokoski et al. (Isokoski and MacKenzie, 2003) combined the PLP and theoretical upper limit predictions to describe the development of text entry rates from users' first contact to asymptotic expert usage. Their proposed combined model makes comparing text entry methods easier.

3.6 CONCLUSION

In the first part of this chapter, I gave an overview about skill acquisition on psychology and cognitive sciences. I described that when people learn new skills, they exhibit similar behavioral characteristics that can be identified with distinct stages of learning. The most widely accepted and used model of learning proposed by Fitts consists of three stages: cognitive stage, associative stage and autonomous stage. Then, I described the power law of practice to state that as practice continues, the time required to perform certain tasks will subsequently reduce. Finally, I discussed different interaction techniques designed to facilitate skill acquisition and improve user's performance while performing text entries' tasks. In the next chapter, I will explain the transfer of skill from one task to another, and its consequences.

4 TRANSFER OF SKILL

The study of transfer is the study of how the acquired skill in one situation applies, or fails to apply, in other situations (Singley and Anderson, 1989). The main purpose of any learning or skill acquisition is that the persons who acquire some knowledge or skill in a formal and controlled situation like a training situation, will be able to transfer such knowledge and skill to real life situations and adapt themselves more effectively.

This chapter provides definitions, factors, theories and models related to the transfer of skills from cognitive psychology literature. It begins with an overview on positive, negative, proactive and retroactive transfer of skills. Then it discusses the theories trying to explain the transfer between two skills. Under the Identical Elements theory, the degree to which two skills are similar determines the efficacy of transfer. In the next chapters, I investigate retroactive transfer phenomena through different qualitative and quantitative analysis.

4.1 DEFINITIONS

4.1.1 *Transfer*

Transfer refers to the influence of learning one skill on the performance of another skill (Gick and Holyoak, 1987). For example, learning mathematics prepares students to learn physics, learning to play rollerblading may prepare one for better ice skating, and experience typing with a English keyboard layout QWERTY may help a person later to learn more quickly to type with a French keyboard layout AZERTY. Transfer is a key concept in learning theory, which generally aims to convey skills (Mayer, 2002; Perkins, Salomon, et al., 1992). The ultimate goal of transfer has been to improve users' performance by applying the acquired skills in similar contexts with shared elements and features, and to extend that learning to the new skills (Hendrickson and Schroeder, 1941).

In addition to transfer from one skill to another skill, transfer can occur from one context to another context (Perkins, Salomon, et al., 1992). In this case, transfer is beyond the original ordinary learning, and called *desired transfer* (Hajian, 2019). For example, airline pilots spend many hours training in flight simulators using a virtual reality (VR) environment to experience a range of scenarios in complete safety. A user may have very good performance with VR flight simulators (ordinary learning) but not as a pilot in a real flight (the desired transfer[1]). Accordingly, in this situation, the learning process cannot be completed unless the transfer of skill from VR to physical environment occurs.

Transfer has attracted researchers' attention in various fields (e.g., psychology, neuropsychology, computer science, motor control, etc.) and many studies have been conducted in different domains, such as education (Bransford et al., 2000; Soini, 1999), linguistics (Jiang and Kuehn, 2001; Odlin, 1989), VR (Boyle and Lee, 2010; Lehmann et al., 2005), and interactive system (Jokinen et al., 2017; Ramesh et al., 2011a). In overall, transfer of skill can be classified into two types: positive and negative.

4.1.2 *Positive transfer (or Facilitation)*

When experience of one skill enhances the level of performance in a new skill, transfer is said to be positive. Thus, in *positive transfer* or *facilitation* some part of the learned skill has a beneficial effect on the performance of other skills. The degree of positive transfer could be strong or minimal, but as long as some improvements are observed in the new skill, it is considered as a positive transfer (Edwards, 2010). For example, learning a second language that is closely related to the first language is considered easier than learning a non-related language. This example also can be applied to the learning programming languages. Learning second (and subsequent) programming languages is easier than learning a first programming language because many concepts and constructs are shared (Scholtz and Wiedenbeck, 1990b).

4.1.3 *Negative transfer (or Interference)*

When learning one skill negatively influences the learning of another skill or of the same skill in a new context, we say that *negative transfer* or *interference* occurs. For example, there is negative transfer from tennis to badminton. Although the two skills seem similar and we might expect positive transfer, learning one of these skills typically reduces the learning of the other. Interference causes a disturbance and interruption typically in the initial stages of learning a new task (Perkins, Salomon, et al., 1992). However, through practice and experience over later stages of

[1] It also called *target context*; the environmental situation in which a person wishes to perform a particular skill as a result of practice (Edwards, 2010).

learning, the impacts of interference can be reduced and even eliminated.

Whether transfer is negative or positive, we distinguish either *proactive* or *retroactive* transfer.

4.1.4 *Proactive transfer*

Proactive transfer (Schmidt and Lee, 1988) refers to the gain or loss of performance with the ***New*** method N as a result of practice with the ***Previous*** method P on a given task (Figure 18b). Negative proactive transfer is also called as anterograde interference for visuomotor learning (Krakauer, 2009; Krakauer et al., 2005, 2006; Wigmore et al., 2002). In this case we say that practicing P *interferes* with the learning of N[2].

4.1.5 *Retroactive transfer*

In contrast to proactive transfer, retroactive transfer is the influence of the *new* skill on the acquisition of a *previously* learned skill (Bunch, 1946; Postman, 1971). *Negative* retroactive transfer occurs when the skill learned later disrupts retrieval of the skill learned earlier. Negative retroactive transfer is also known as *retroactive interference* (Edwards, 2010; Schmidt and Lee, 1988), retroactive inhibition (Briggs, 1954; Bunch, 1946; Johnson, 1933; Muller and Pilzecker, 1900), after-effects (Bastian, 2008; Malone et al., 2011), retrograde interference (Krakauer, 2009; Krakauer et al., 2006; Wigmore et al., 2002), catastrophic interference (Robins, 1995) or catastrophic forgetting (French, 1999; Goodfellow et al., 2013).

Retroactive transfer has been investigated in contexts including free recall (Briggs, 1954; McGeoch and Irion, 1952), visual perception (Mareschal et al., 2002), language acquisition (Pallier et al., 2003), machine learning (Coop et al., 2013), motor learning of discrete (Koedijker et al., 2010) or continuous movements (Brashers-Krug et al., 1995; Healy et al., 2011), visuomotor learning (Krakauer et al., 2005), advertisement (Burke and Srull, 1988) and games (Gray and Berry, 2018b).

4.1.6 *Related concepts*

I distinguish three concepts related to retroactive transfer which are more often studied in HCI.

[2]Zero transfer is also possible when the practice of P has no effect on the use of N (Edwards, 2010)

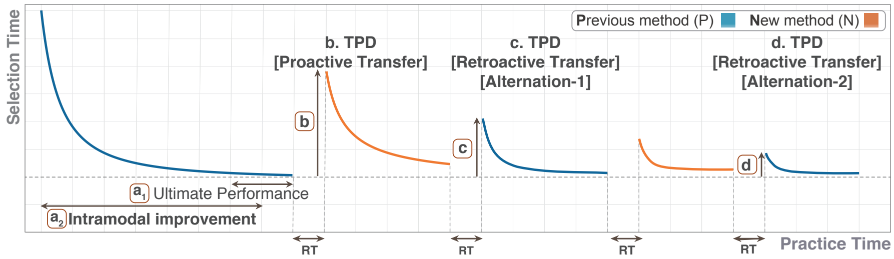

Figure 18: Conceptual model illustrating the alternation between a previous method (P) in blue and a new method (N) in orange color, as well as the corresponding phenomena: (a_1) Ultimate performance, (a_2) Intramodal improvement, (b) Proactive transfer, (c) Retroactive transfer (first alternation) and (d) Retroactive transfer (second alternation). Temporal performance drop (TPD) indicates the temporal difference between the end of one method and the beginning of another method. Rest time (RT) shows the interval time between learning of two methods.

4.1.6.1 *Task switching*

People frequently perform multiple tasks in the same time period, called multi-tasking, task switching or task interleaving. There are two problems associated with task switching: the amount of time it takes and the mental complexity of remembering how to invoke the other task and of trying to get into previous mental context, such as working on a project, then switching to email before returning to the project (Card and Henderson Jr, 1986).

Task switching is well studied in HCI (Czerwinski et al., 2004; González and Mark, 2004; Iqbal and Horvitz, 2007; Warr et al., 2016) but differs from retroactive interference in that it refers to a temporary distraction (e.g. a notification when writing a document) rather than a learned skill. Moreover, the tasks are categorically different, though the same interface is usually used for both. In retroactive transfer the tasks can be the same, or differ little, and the interface change is the source of the confusion.

4.1.6.2 *Deskilling*

Deskilling refers to manual skill degradation through the use of automation. Deskilling is a familiar theme in the psychology and sociology of work going back to the first industrial revolution. It is often a consequence of technological advancements and organizational change. Through the process of deskilling, skilled workers are eliminated by the introduction of technologies operated by semiskilled or unskilled workers. However this results in cost savings due to lower investment in human capital, the workers can lose their psychomotor and cognitive skills (Carroll, 2003; Christoffersen et al., 1996). For example loosing of the manual driving skills when operating advanced automated vehicles is a byproduct of vehicle automation (Trösterer et al., 2016). In addition to vehicle automation, deskilling can occur for the pilots on highly automated flight. They are needed to take over from the automation in cases of failure or undesired system behavior. One problem with this task allocation is that, over time, continued and extensive use of automation can lead to overreliance on technological assistance and the loss of cognitive skills required for manual flight. Thus, in those circumstances when pilots need to manually control the airplane, they may struggle, especially since they are now required to manually control a system that is not functioning properly (Sarter et al., 1997). Deskilling can also lead to a "vicious cycle" of performance degradation (Parasuraman and Riley, 1997) when pilots realize of their deskilling, it leads to even heavier reliance on automation (Ferris et al., 2010). Unlike deskilling, in retroactive interference both tasks are manually controlled.

4.1.6.3 *Tetlag*

Tetlag (Gray and Berry, 2018a; Gray and Berry, 2018b) has been inspired by the Tetris game community, and refers to the brief period of confusion when switching between different versions of the popular game with different rotation rules and other behaviors. Some gamers regularly alternate Tetris versions (i.e., between normal version of Tetris and the upside down version of the game), just as some users regularly alternate computer operating systems, e.g. Mac and Windows, resulting in a brief adjustment period. Tetlag seems like task switching but studies of task switching look at switch costs over the course of 100 to 800 of milliseconds (Altmann and Gray, 2008), but switch costs in TetLag are measured in minutes, hours, and days. A key difference of Tetlag from retroactive interference is that the two interfaces in Tetlag are *both very well-learned* and their alternation is a common occurrence.

4.1.7 *Transfer measurement*

The amount of transfer is measured by the methods illustrated in Table 2. In this design, two groups of participants matched on age, education, intelligence and prior learning and also background are selected. One of them is designated as an experimental group and the other as the control group and they are compared on the transfer criterion. For measuring proactive transfer, the experimental group practices one skill (Task A), and then a second skill is practiced (Task B). The control group practices only Task B. Through this test, we aim to understand whether practice of Task A will have an influence on the experimental group's performance when practicing Task B. For example any inferiority in the performance of the experimental group could be attributed to the negative effect of transfer from learning task A.

By conducting a retroactive transfer test, we aim at understanding whether a skill practiced on task B after the skill of task A will influence subsequent performance of task A. For example, if the participants of experimental group have more errors than the control group that only perform task A, then retroactive interference has happened (Coon and Mitterer, 2012).

4.2 THEORIES

One challenge is to predict whether transfer would be positive or negative from one task to another (Kieras and Bovair, 1986b; Osgood, 1949; Royer, 1979; Taatgen, 2013). Explanations of why transfer occurs (or fails to occur) were typically based on the theory of Identical Elements and expressed in form of **s**timulus-**r**esponse (S-R) language of interference theory. The interference theory research uncovered important phenomena about transfer (primarily negative transfer) and forgetting (primarily retroactive interference).

4.2.1 *Identical Elements theory*

Thorndike and Woodworth propose the Identical Elements theory in 1901 (Woodworth and Thorndike, 1901). They suggested that transfer from one task to another would only occur when

Proactive interference

Experimental group	Learn A	Learn B	Retention test B
Control group		Learn B	Retention test B

Retroactive interference

Experimental group	Learn A	Learn B	Retention test A
Control group	Learn A	Rest	Retention test A

Table 2: Testing methods for proactive and retroactive interference.

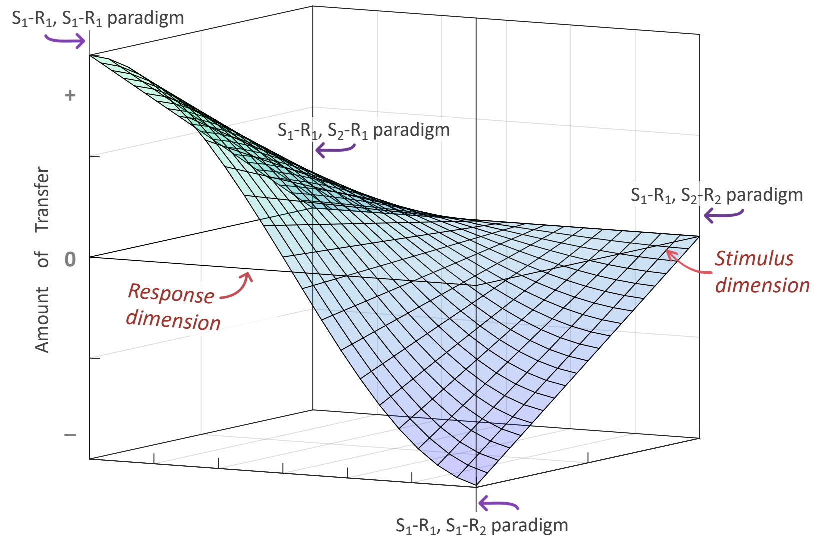

Figure 19: Osgood's transfer surface.

both tasks shared *identical elements*. For example, the only reason why it is easier to learn French after Latin, is that many words in Latin are similar in French (Taatgen, 2013). Further, they proposed that the greater the number of shared elements, the greater the amount of transfer. What they meant by the term "elements" was shared features of the stimulus of the two tasks. Thus, two tasks which share some set of stimulus features are possible candidates for transfer (Royer, 1979).

Theory of Identical Elements by Thorndike and Woodworth has influenced many of the subsequent theories of transfer. For example, Osgood (1949) (Osgood, 1949), formalized what was known about transfer at the time in his influential research on "the transfer and retroaction surface", Figure 19. He indicated that facilitation and interference in transfer were related to the similarity and difference relationships between stimuli and responses in a previous and new task. Osgood (Osgood, 1949) showed how the amount of transfer is influenced by similarity during paired-associate list[3] learning. Paired-associate learning involves the pairing of two items: a stimulus and a response. For example in the QWERTY keyboard layout, a character (i.e., stimulus) like Z and its key location (i.e., response) like (2,0) on the keyboard are paired,

[3]Paired-associate learning is a classic memory paradigm that is used to understand how people encode and retrieve newly formed associations among stimuli. In a typical study using paired-associate learning, people are asked to learn unrelated word pairs (e.g., stove–letter). At a later time, memory for those pairs is typically tested by having them recall one of the words in response to the word it was paired with during encoding (e.g., recall the word that was paired with "stove")(Arndt, 2012)

and when the learner is prompted with the stimulus, she responses with pressing the appropriate key's location, Z(2,0). The mentioned surface draws the amount of transfer as a function of the amount of similarity between stimulus and response:

$$A_t = f(S_r, S_s) \quad (7)$$

where A is the amount of transfer, S_s is the amount of similarity between stimuli and S_r is the amount of similarity between responses. A can be positive (positive transfer) or negative (negative transfer). Positive transfer reflects savings in learning new task and negative transfer reflects interference. According to the transfer surface, interference increases when the stimuli in both layouts are identical, but the responses are different (Dey, 1969), (e.g., similar keys Z in both layouts P and N), but different locations (i.e., $Z(2,0)$ in layout P and $Z(0,1)$ in layout N).

Likewise, Ellis'(1965) (Ellis, 1965) followed the essential details of the theory of Identical Elements and simply updates the generalization contained in Osgood's study. He argued that transfer is maximized when a variety of similar learned stimuli are employed in new task. Thus, stimulus generalization occurs when a response learned in the presence of a particular stimulus is also elicited in the presence of a similar stimulus (Royer, 1979). Theory of Identical Elements, and the subsequent elaborations of that theory, describes the boundary conditions of most situations. However, this theory still lacked precision on what exactly is an element, and when are two elements truly identical? Such a lack of definition has made the theory difficult to test and interpret. Singley and Anderson (1989) proposed a modern version of the theory to clarify these lack of precision (Singley and Anderson, 1989; Taatgen, 2013).

4.2.2 *ACT theory of transfer*

Singley and Anderson (Singley and Anderson, 1989) restore the Identical Elements' theory of Thorndike from the perspective of cognitive psychology. Making use of knowledge-representation language, they recast his elements into units of procedural and declarative knowledge in the ACT theory of skill acquisition (Anderson, 1983). ACT is a cognitive theory about how human cognition works and made of memory modules: *declarative memory* which is represented in structures called chunks, consisting of facts such as 2+3=5, and *procedural memory*, made of productions. Productions represent knowledge about how we do things, for instance knowledge about how to type the letter "R" on a keyboard.

Singley and Anderson in their theory of transfer developed the production rule as the element of transfer, and used the number of identical productions between two tasks as a measure of potential transfer. As a demonstration of this approach, they examined transfer between text editors. In one of their experiments, subjects had to learn to edit text using one of three editors, and then switched to a different text editor. The experiment demonstrated substantial transfer between text editors. According to ACT theory of transfer, the greater the production overlap, the greater the transfer. Thus, transfer is a matter of taking task-specific knowledge from one task and using it for another, semantically similar, task (Koedinger et al., 2016; Taatgen, 2013).

4.2.3 *Transfer-appropriate processing theory*

The next theory discussed in this chapter is Transfer-appropriate processing proposed by Bransford et al. in 1979 (Bransford et al., 2014). This theory is analogous to Identical Elements theory from some aspects but argues that transfer effects depend on the similarity of cognitive processing features between skills and not so much on how elements are related. In this theory, the transfer is positively related to similarities in mental operations shared by the skills. For example, problem-solving skills, speed of decision making, attentional focus, and the application of rules that are shared between skills, determine the degree of possible transfer (Edwards, 2010).

Concluding the discussion of theories, leads to a general observation. Schmidt and Young (Schmidt and Young, 1987) identified that research does not support strong transfer effects except when two skills are very similar. The term near transfer is often used to explain such transfer effects between similar skills. Far transfer refers to transfer effects between skills that are dissimilar and do not share many common elements. Therefore, the "nearer" two skills are in shared common elements, the greater will be the amount of transfer between the two. Generally, similarity between skills facilitates transfer, at least to some degree. When two skills are similar in common elements, however, negative transfer is frequently observed between them at least initially.

4.3 FACTORS

Proactive transfer depends on several factors such as the amount of practice, the nature of the task, the rest time (Edwards, 2010), or the similarity between the previous and new methods (Schmidt and Lee, 1988). However, since retroactive transfer is the main focus of this thesis, in the following I identify these factors considering their effects on retroactive transfer.

4.3.1 *Practice*

One major factor influencing retroactive transfer is the amount of practice of the previous and new method (A. Schmidt and Nacson, 1971; Brashers-Krug et al., 1995; Lewis and Miles, 1956). Although increasing practice time of the new method seems to increase interference, increasing the practice of the previous method seems to be context sensitive. While some studies found that increasing the learning of the previous method reduces the interference (Lewis and Miles, 1956; Panzer and Shea, 2008), others found the opposite (A. Adams, 1987). Notably, the practice does not necessarily need to be physical (i.e. repeating a physical movement), but can be also mental. For instance, Wohldmann shows that mental practice can reduce the retroactive interference (Wohldmann et al., 2008). Moreover, the *distribution* of the amount of practice can also have an impact of retroactive transfer (Healy et al., 2011).

4.3.2 *Similarity*

Only few studies focused on controlling the similarity factor for retroactive interference (Healy et al., 2011). As stated above, Osgood (Osgood, 1949) showed that the amount of retroactive transfer is affected by similarity during a paired-associate task learning. According to the Osgood's theory of learning transfer, retroactive interference increases when the stimuli in both layouts are constant but their responses differ.

Similarity is a relevant factor to HCI as designers can more easily manipulate it. Several optimization methods have been proposed to maximize both the performance of the new layout and its similarity with the previous layout (Bailly et al., 2013; Bi and Zhai, 2016; Bi et al., 2010; Dunlop and Levine, 2012; Oney et al., 2013; Zhai and Kristensson, 2003). Similarity is defined as the number of identical elements shared in the two methods (Cormier and Hagman, 2014; Edwards, 2010).

4.3.3 *Rest time*

The time interval between the learning of two methods can also influence retroactive transfer (Bunch, 1946; Schmidt and Lee, 1988). More precisely, when the retention test was immediate (short rest time), they attribute retroactive interference to recency effects, but when the retention test is delayed (long rest time), the original response is more likely. When time is delayed overnight, it further fosters consolidation (Ficca et al., 2000) and can also play a role in the magnitude of the transfer (Healy et al., 2011; Krakauer et al., 2005). Previous research clearly shows that the human brain needs downtime between different learning experiences in order to undertake the necessary processes and begin to make new memories of the newly experienced material (Doyle and Zakrajsek, 2018).

4.3.4 *Task*

The nature of the task, recognition-based vs. recall-based also influences the retroactive transfer (Anderson and Neely, 1996): In cognitive memory tests of retroactive transfer, participants experience several memory deficits in recall tests, but retroactive interference is almost completely eliminated with the recognition tests (Anderson and Neely, 1996).

4.4 models

4.4.1 *Proactive transfer models*

Several models of proactive transfer have been proposed (Jokinen et al., 2017; Kieras and Bovair, 1986a; Monsell, 1978). Jokinen et al. (Jokinen et al., 2017) recently presented a model aiming to explain the negative impact of keyboard layout change on typing performance. This model relies on some important components of the cognitive architecture of ACT-R. It predicts visual search time for a given key's location on a partially changed layout based on the interplay of four components: vision, visual short-term memory, long-term memory and controller.

An overview of the model's components is given in Figure 20. The input to the model is a keyboard layout, defined as locations of keys (x,y). The next inputs are the starting location for searching the target key. It outputs a sequence of (x, y) locations of eye fixations, along with the total search time for a key.

The model uses at first the visual search component to encode the given key, then encoded key location is placed in the visual short term memory and finally it will transit to long term memory. The key aspect, regarding skill transfer, is the use of a utility learning mechanism to decide between conflicting entries (the old and the new one) in the long-term memory.

When the users encounter new or partially changed keyboard layout after learning the first layout, it assumes that there is a

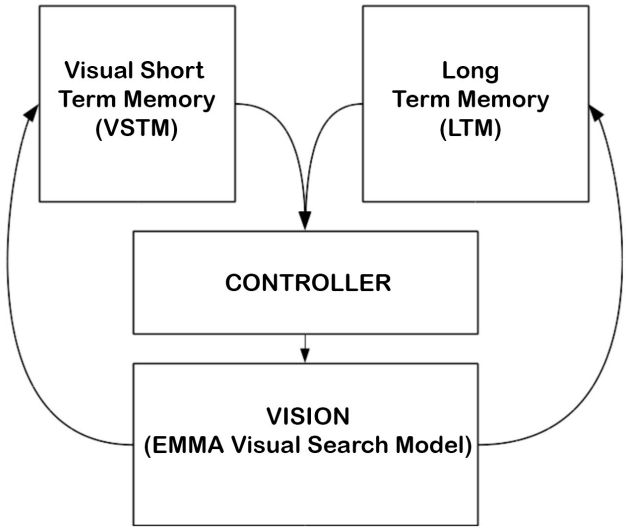

Figure 20: The model of Keyboard layout learning (Jokinen et al., 2017)

competition between conflicting entries. Thus, the authors used a *controller* to retrieve the key's location from long-term memory. As more than one response (key's location) can match the stimulus (the key's letter) in long-term component, they propose to use the *utility learning* in their model. In this case the key with the highest utility is selected over another. The utility can be learned from experience and reward.

If $U_i(n-1)$ is the utility of a key i (i.e., key is a pair of (character, location)) after its $n-1$st recall, and $R_i(n)$ is the reward the key receives for its nth recall, then its utility $U_i(n)$ after its nth recall will be given by the difference learning equation:

$$U_i(n) = U_i(n-1) + \alpha[R_i(n) - U_i(n-1)] \tag{8}$$

where α is the learning rate around 0.2, and the initial utility is equal to zero when a new key is first recalled (Anderson, 2009b; Jokinen et al., 2017). Here, $R_i(n)$ is calculated as the temporal distance between the recall and finding of the target.

The result of this model, as can be seen in Figure 21 left, shows the average key search times decrease as the model learns a QWERTY layout. After the swapping of four keys, the search time immediately increase to learn the new locations, but again it can decrease up to the ultimate performance.

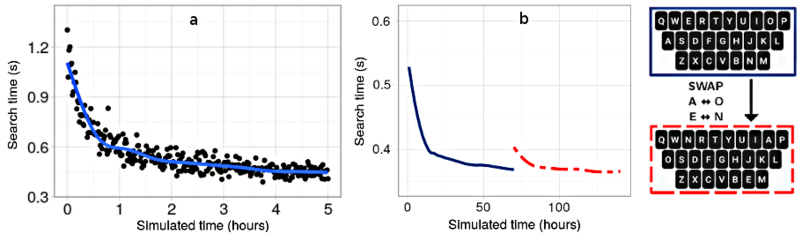

Figure 21: Prediction of how users learn the locations of keys on a new keyboard and on a partially changed keyboard. Adapted from (Jokinen et al., 2017)

We need to consider that in ACT-R there are two memory stores for two types of knowledge: a declarative memory module that stores factual knowledge about the domain, and a procedural memory module that stores the system's knowledge about how tasks are performed (Peebles and Banks, 2010). Declarative knowledge is represented in a structure called chunk. Each chunk (e.g., key Z(0,2) in a old layout is a chunk) has a level of activation which determines its availability for retrieval, the level of which reflects the recency and frequency of its use. Only chunks that exceed a certain amount of activation, as defined by the retrieval threshold, can be retrieved. The activation equation is the following:

$$A_i = B_i + \varepsilon \qquad B_i = \ln\Big(\sum_{j=1}^{n} t_j^{-d}\Big) \tag{9}$$

This equation shows B_i for a chunk i, where n is the number of presentations for a chunk i, t_j the time since the jth use and d the decay parameter (Veksler et al., 2014). As presented in (Anderson and Schooler, 1991), activation value allows models to predict the retrieval and forgetting of a chunk.

Moreover, procedural knowledge is represented as rules called productions. Production can be represented in the form of "IF <condition> THEN <action>" rule. For example to type a key on a keyboard there are at least two production rules: 1) IF a letter is displayed on the screen, THEN its location will be retrieved from memory and 2) IF the location has been retrieved, THEN the letter can be typed. These rules are representing the skill of typing. Each productions is associated with a utility, which are responsible for determining which productions get selected when there is a conflict.

The Jokinen's model assumption is not inline with the components of the cognitive architecture of ACT-R, as a chunk of key and its location is a declarative knowledge, and only can be compared to another chunk using their activation values. Since finding a key in a keyboard reflects the declarative memory, there are no competing production rules. Therefore, when there are two conflicting entries, the key with more activation is returned and there is no need to use the utility equation.

I come back to this model in the final chapter of this thesis as some components could be used to model retroactive transfer phenomena.

4.4.2 *Retroactive transfer models*

I am not aware of retroactive models in psychology literature.

4.5 INTERACTION

4.5.1 *Proactive transfer in text entry*

Proactive transfer has received a lot of attention in different domain of HCI (Lafreniere and Grossman, 2018; Ramesh et al., 2011b; Scholtz and Wiedenbeck, 1990a), specially in text entry (Jokinen et al., 2017; Matias et al., 1993; Polson et al., 1986). Users want to build on previous knowledge when learning a new interface. For example, Half-QWERTY is an one-handed typing technique on a special half keyboard, designed to facilitate the transfer of two-handed typing skill to the one-handed condition. It has been reported that QWERTY touch-typists reached 50% of their full QWERTY speed in a relatively short period of time (8 hr) in a Half-QWERTY layout (Matias et al., 1993).

Similarity, as one of the main influential factor in transfer, appears to be critical for interaction design (Schmidt and Lee, 1988). Polson et al. (Polson et al., 1986) showed better skill transfer in text editors when there is a high level of similarity between the two tested interfaces. In contrast, switching from a QWERTY to an AZERTY keyboard layout can introduce some interference even with a few key differences between these two designs (Berard and Rochet-Capellan, 2015; Koedijker et al., 2010). Consequently, several novel keyboard layouts manipulated the similarity factor to optimize performance with the traditional QWERTY layout (Bi and Zhai, 2016; Bi et al., 2010; Dunlop and Levine, 2012; Oney et al., 2013; Zhai and Kristensson, 2003). These studies showed the evidence that users rarely want to spend the time needed to learn a new keyboard layout. Thus, based on these evidences, Chun Yat Li et al. (Li et al., 2011) leverage the QWERTY keyboard layout instead of using different layouts and input modalities to design their 1line keyboard layout. It is a soft QWERTY keyboard that is only 40% of the height of the native iPad QWERTY keyboard. Their keyboard condenses the three rows of keys in the normal

QWERTY layout into a single line with eight keys. Through an evaluation, they showed that participants are able to quickly learn how to use the 1Line keyboard and type at a rate of over 30 WPM after just five 20-minute typing sessions.

4.5.2 *Retroactive transfer in HCI*

In HCI, retroactive transfer has received only little attention. In the comprehensive book Human Computer Interaction: Fundamentals (Sears and Jacko, 2009) retroactive interference is only briefly mentioned as a false memory phenomenon (Proctor and Vu, 2007). One exception is the study of Walker & Olson (1988) who investigated proactive and retroactive transfer of command shortcuts in two text editors (Walker and Olson, 1988). While they did not observe proactive transfer, they observed a retroactive transfer effect between the two sets of shortcuts (emacs and express). express appeared more robust to interference than emacs. However, in this study, participants did not perform a visual-motor learning task involved with an interactive system as they did *not* execute the memorized shortcuts (they wrote them on paper).

4.6 conclusion

In this chapter, I gave an overview about transfer of skill on psychology and cognitive sciences. I described that learning of one skill often has an effect on the learning of other skills, a phenomenon called transfer. It can be categorized as proactive or retroactive transfer. In proactive transfer the previous skill affect the acquisition of new skill, while in retroactive transfer the new skill influences on the performance of previously learned skill. The negative form of proactive and retroactive is called interference. Retroactive interference occurs because the new information in the memory interferes with retrieval of old information. Retroactive interference is less investigated in HCI. Hence, in this thesis I focus mainly on retroactive transfer phenomenon. In the next chapter I described an introspection and two rounds of interviews conducted to understand retroactive transfer scenarios in HCI.

Part II

PROBLEM DEFINITION & DATA COLLECTION

5 RETROACTIVE TRANSFER IN REAL-WORLD

Working life today regularly requires people to switch between interfaces to complete a single task or a project. For instance switching between programming languages is something that happens to every programmer. They have to write a program in C++, then another project is in C, then they are programming in Java, then they are programming again in C++[1]. Another example is a graphists trying to create one file, but using illustrator and photoshop interchangeably. Illustrator, is much easier to work with when creating graphics (as far as strokes, type, live color, etc.) and photoshop proves to be necessary for editing rasterized images, clearing background, cropping, etc [2].

Alternating between interfaces are likely to affect user's performance as users have to learn or relearn how to use the current interface and can experience negative proactive and retroactive interference.

In order to understand the retroactive transfer phenomena when using interactive systems, I conducted the qualitative studies. First, I performed an introspection through my personal experience in using text entry. This introspection was at the origin of this thesis. Then, I run an interview-based study with several potential users, who face this phenomena while working with different interfaces. I created and conducted the interview to elicit information from users' experiences to understand:

1. The type of scenarios involving retroactive transfer
2. The reasons why users need to alternate between interfaces
3. The nature of the retroactive transfer (positive, negative or neutral)
4. The strategies to avoid retroactive transfer

Third, I refined the interview-based study with two HCI experts experiencing retroactive phenomena in using text entry. I now report on these two qualitative studies. I use these findings to motivate and design a controlled experiment (described in the

[1] check this link for more examples of the coders that switching between different languages: https://www.quora.com/Is-it-weird-for-programmers-when-they-switch-between-languages

[2] The example reference: https://graphicdesign.stackexchange.com/questions/16914/working-in-illustrator-photoshop-interchangeably

next chapter) to investigate user performance after experiencing a retroactive transfer.

5.1 INTROSPECTION

Introspecting through my personal experience in using text entry helped me to better clarify retroactive transfer phenomena.

5.1.1 *Methods*

Introspection is a self-observation with the intent to learn more about the self by describing current thoughts, feelings and activities (Gould, 1995). Introspection is the opposite of extrospection (Valsiner, 2017), the observation or examination of things external to one's self.

As experiential beings, the people introspect in everyday life to profound self-awareness and self-understanding when interact with the external world. Interaction designers and researcher also take advantage of this technique to learn about the user's perspective, internal state and interaction with interactive systems (Wagenknecht, 2017).

When you are aware of an ongoing experience and searching for answers for such questions by thinking [3]:

- What did you want to do? (*goal*)
- How did you interact with the system? (*user action*)
- How did the system react? (*system response*)
- Did it do what you expected? (*comment*)
- Highlight breakdowns, bugs, unusual positive or negative events. (*surprises*)

you are introspecting, though it often happens in an automatic and unstructured way (Xue and Desmet, 2019).

It is necessary to consider that introspection is not a valid *scientific* approach (Xue and Desmet, 2019). However, it can be a valid design technique, as long as it provides useful perceptions to investigate experiential aspects to go beyond a purely functional view of the system.

[3] The source of self-reflective questions: https://ex-situ.lri.fr/content/1-workshops/6-hci-bootcamp-2018/1-handouts/doit-book-method-introspection-oct.pdf

5.1.2 *Finding*

My mother language is Persian and I communicate with my family using Persian keyboard layout. On the other hand, my laptop's keyboard has an English QWERTY layout which I used at work for programing, writing and emailing. I am based in France and in addition to my research activities, I have some teaching courses wherein the keyboards of workstations are in French AZERTY keyboard. Therefore in a typical day I use several keyboards with different layouts and multiple times per day.

Although these keyboards share a lot of similarities and globally have the same geometry, there are some key differences in the QWERTY and AZERTY keyboard. Personally, the problem appears when alternating between two similar keyboard layouts (i.e. QWERTY and AZERTY) but not between Persian and QWERTY layouts that have very few common features.

The result of self-introspection gave a deeper understanding of the occurrence of negative retroactive transfer. It encouraged to think about the impact of alternations on performance, in particular the impact of similarity between two interface on the performance change. This experience of retroactive interference were made explicit when working on a model of proactive transfer with keyboard. I thus decided to further investigate this phenomenon by conducting interviews and extending the scope (from keyboard to interactive systems).

5.2 INTERVIEW 1: GENERAL EXPERIENCES OF RETROACTIVE TRANSFER

5.2.1 *Methodology*

In this qualitative interview, the initial methodology was to use questions deliberately broad and open-ended. Qualitative interviews might feel more like a conversation than an interview to respondents, but the researcher is in fact usually guiding the conversation with the goal in mind of gathering information from a respondent. Open-ended questions do not provide answer options. They are more demanding than closed-ended questions, because they require participants to come up with their own words, phrases, or sentences to respond (Bernard and Bernard, 2013). The questions of this interview aimed at understanding the impact of switching between two interfaces on the user's performance. Participants are asked to compare the performance with the interface P before and after using the interface N, in order to realize how the interface N interfered with the learning of interface P (i.e. $P \rightarrow N \rightarrow P$).

However, this methodology did not appear informative in pilot study. Indeed, the difficulty in extracting incidents of retroactive transfer is that participants need to recall a fairly complex combination of sequential actions. First, they need to recall their performance level while using a previous interface P, recall interacting with a new interface N for a certain period and, finally, recall their performance when returning back to previous interface P. I thus decided to adopt a *semi-structured* methodology, with several memory aids in this interview. In a semi-structured interview, there is a general outline, but may different questions have been asked (Fontana and Frey, 1994). The interviewer has a particular topic about which response would like to be heard, but questions are open ended and may not be asked in exactly the same way or order to each participants. In in-depth interviews, the primary aim is to hear what the interviewee thinks is important about the topic (Bernard and Bernard, 2013).

I conducted the study in participants' working environment to aid the recall of relevant situations. I explained to participants the concept of retroactive transfer by using the example of a person alternating between right-side and left-side driving when changing countries. I emphasized that I am interested to know what happened to their driving performances once they returned back to their hometowns. I emphasized the fact that the "transfer" can be positive, negative or neutral to not bias participants. I finally explained the goal of the interview as to see if similar phenomena occur with their interactive systems (e.g. mobile phone and computer).

The interview was audio-recorded, lasted about 1 hour and then analyzed using annotations and timestamps on Camtasia(). The time-stamped notes were further analyzed in spreadsheet software to help index episodes of interest.

5.2.1.1 *Sample scenarios*

I showed the participants a printout of interface examples' images. I picked general and most common interfaces that can be adapted to a range of situations as well as different users. But they were free to discard the scenarios which do not apply and/or report alternative scenarios. The scenarios included (the category is inspired by (Foley et al., 1984)):

Pointing
Alternating among different *mouse devices* using different mouse

or touch-pad device, or the same mouse but with different behaviour e.g., the cursor reacts differently, i.e. mouse acceleration, Figure 22.

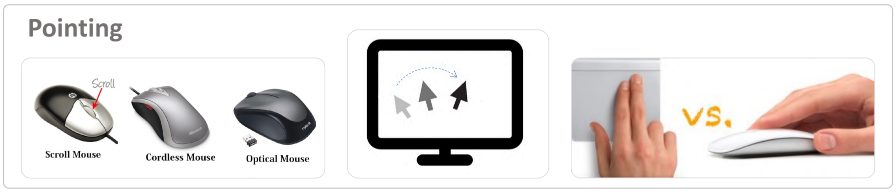

Figure 22: Examples of sample scenarios: different input devices for the same task.

Command selection

-Alternating between different *keyboard shortcuts* e.g. to use different shortcuts for the same commands or the same shortcut for different commands, Figure 23.

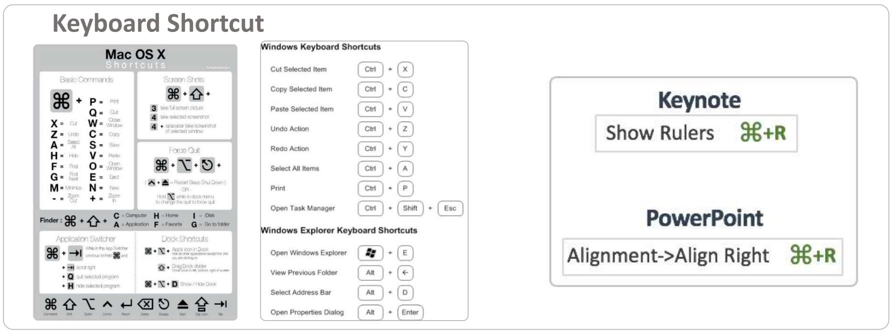

Figure 23: Examples of sample scenarios: same shortcut for different commands

-*Graphical menus* of interfaces that have different item organisations i.e. same items but at different locations(e.g. launch menus on smartphone or two similar applications (Photoshop / GIMP) on desktop, or item locations on websites, etc.), Figure 24.

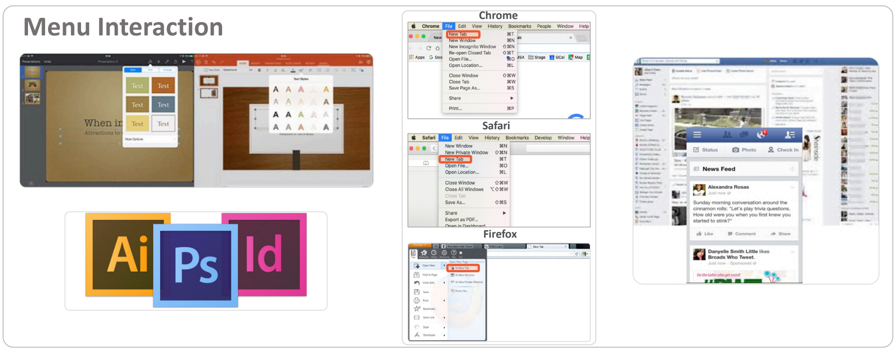

Figure 24: Examples of sample scenarios: different graphical menus.

Gestures
Gestures shortcuts, e.g. different gestures for the same commands or the same gesture for different commands, Figure 25.

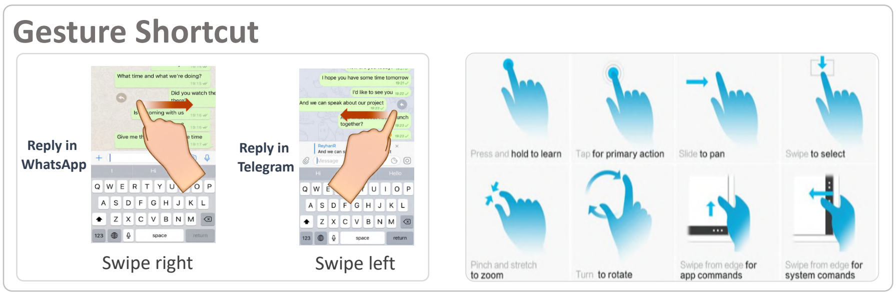

Figure 25: Examples of sample scenarios: left, different gestures for the same command and right, set of gestures.

Text input
-Keyboard devices with different *shapes* (e.g. portrait vs. landscape on a smartphone), or keys which are larger or smaller (e.g. Return key), Figure 26 left.

-Keyboard devices with different *key organizations* (e.g. French (AZERTY), American (QWERTY)). They have different position of letter keys, but also of special keys such as Ctrl, Shift, Return, etc, Figure 26 right.

Figure 26: Examples of sample scenarios: left, the same keyboard device with different shapes; and right, different key organizations in similar keyboard layouts

Operating systems
Different *operating systems*, e.g. Microsoft Windows, Apple macOS, Linux, etc, Figure 27.

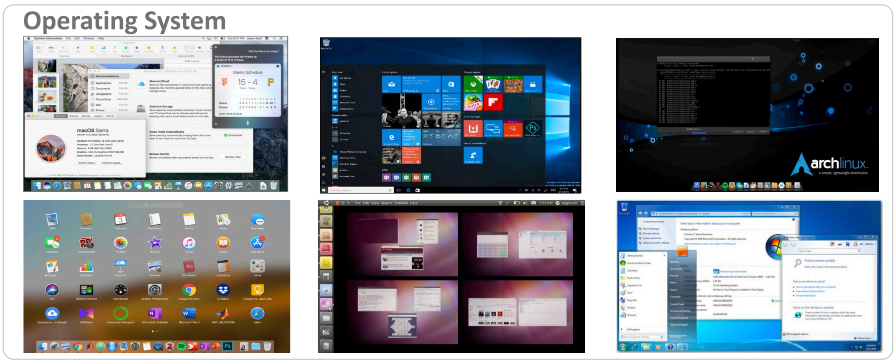

Figure 27: Examples of sample scenarios: switching among different operating systems

Application and programming language

-Switching among different *release versions* of the same app (i.e. different versions of IDEs, Matlab, Photoshop), Figure 28.

Figure 28: Examples of sample scenarios: different versions of the same app.

-Switching among *different platforms* for the same application. (i.e. Microsoft excel for Windows/macOS or for Mobile, or Gmail in PC and Mobile), Figure 30.

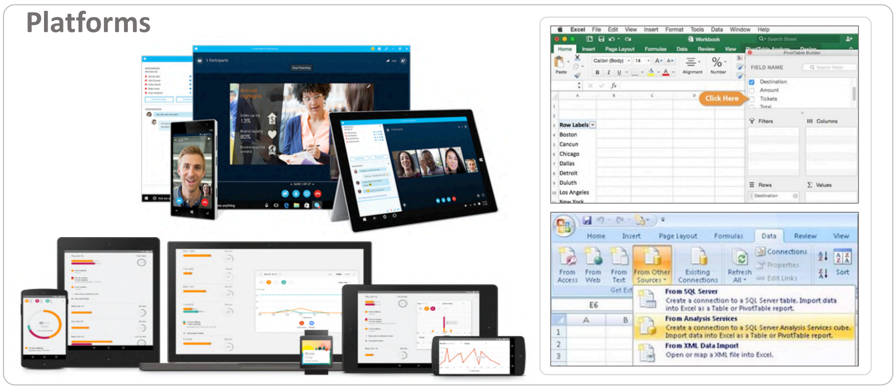

Figure 29: Examples of sample scenarios: switching among different platforms for the same application.

-Alternating between different *programming languages* (e.g. Java, Python, etc.), Figure 30.

Figure 30: Examples of sample scenarios: switching among different programming languages. Hello World in different programming languages.

5.2.1.2 *Participant*

I interviewed 6 adults (< 40 years), 4 male, 2 female, 4 French, one Australian and one Taiwanese. Two were professional programmers in different application areas: embedded systems and haptic devices. The other 4 were researchers in different domains: medical, bio-mechanics, information theory, and sociology (Table 3), (Table 4).

ID	Gender	Origin	Occupation
1	Male	French	Professional programmer in embedded systems (robotics)
2	Male	French	Professional programmer in haptic devices
3	Male	Australian	Researcher in medical research
4	Female	Taiwanese	Researcher in biomechanics
5	Male	French	Researcher in information theory
6	Female	French	Researcher in sociology

Table 3: Participants' ID and their profiles.

5.2.1.3 *Data collection & analysis*

Participants reported a total of 71 incidents of alternation between **p**reviously (P) and **n**ew (N) interfaces (P $\rightarrow$ N $\rightarrow$ P) which were

ID	Primary OS	Secondary Os	Comments
1	Linux	Windows macOS	Having 3 to 4 even more OS, some with the only command line (LINUX). Using windows, Linux and macOS because he needs to code for different people
2	Ubuntu	Windows	All his computers have a dual boot: Ubuntu and windows, because some applications work only on windows
3	Windows	macOS	Windows at work, macOS at home Strong preferences to do different tasks with each system, but sometimes he works at home.
4	Windows	Ubuntu	Dual boot. Mostly using windows, use Ubuntu only when she obliges. She may use a macOS on somebody else's computer.
5	Ubuntu	Windows macOS	Ubuntu at work. Uses windows to be compatible with his advisor. At home uses the macOS.
6	Ubuntu	Windows macOS	Dual boot Ubuntu and Win. macOs on her husbands computer. Used to have Windows DOS. Uses also macOS since the age of 8.

Table 4: Participants' primary and secondary Operating System (OS).

either negative (33) or positive (18) retroactive transfer. Regarding the 20 remaining incidents, participants could not recall whether there was a change in their initial performance. I summarize my observations using the notation (xi, yp), when one observation appears in *more than one* incidents. x indicates the number of **i**ncidents and the y to the number of **p**articipants. For example, if 2 participants mentioned a total of 5 incidents when typing text, the notation is (5i, 2p).

5.2.2 *Findings*

5.2.2.1 *Why do users alternate between interfaces?*

Some alternations are due to external factors (30i, 6p), such as a programmer who has to code for clients who use different systems. Other alternations occur because of the need to use complementary functionalities between two interfaces (41i, 6p), such as the mobile version of a desktop application. In both cases, the alternation appeared as a necessity rather than a choice.

5.2.2.2 *Positive retroactive transfer*

All participants reported incidents of positive retroactive transfer (18i, 6p), e.g., the new version of Microsoft Office (docx version) was so annoying for a user, so once he came back to the old version, appreciated it more, have better control and felt faster. A common pattern was when interface N highlights an unknown functionality of interface P (13i, 6p), e.g., learning the new language C helped to learn Python (familiar language) in more depth. Another example is the gesture vocabulary (e.g., three fingers interactions) of macOS, as an interference interface, encourage them to try configure this gesture in their primary interface (Linux). In addition they found new functionalities highlighted in the mobile version, which they did not know existed on the windows, and it made them realize improving their performance on windows. Generally with all language alternations, the more interference the better she understands the initial language.

5.2.2.3 *Negative retroactive transfer*

All participants reported incidents involving retroactive interference (33i, 6p). Most of them involved using a keyboard (16i, 6p), for example, when alternating between QWERTY and AZERTY layouts. They reported a drop in their typing speed on their primary keyboard after experiencing the new layout. They also recalled being frustrated with typing errors, especially when executing an incorrect keyboard shortcut, leading sometimes to a "disaster", e.g., executing Ctrl+Q ("quit") instead of Ctrl+A ("select all"). Some participants also reported a retroactive interference while searching for a functionality in a graphical menu (4i, 4p), for instance, when alternating between different versions of the same application. Others reported making more errors with their previously learned programming language after learning a new one (5i, 3p). An expert gamer reported a drop in his gaming performance while alternating his fast mouse at home with his regular mouse device at work.

5.2.2.4 *Retroactive transfer factors*

Several participants spontaneously elaborated on reasons that can increase/reduce the previously mentioned interference. The most pronounced comment that all participants reported was the degree of *similarity* between interfaces as the main root of interference (6p). For example, one user reported that their mouse configuration on Linux is faster then the mouse configuration on windows. So after coming back to windows, it feels faster, which results in making mistakes at the beginning.

Others argued that the *amount of practice* with the new interface is the factor that will determine the amount of interference later on (4p), e.g., practicing new version of Matlab for a long time increases the interference on old version. Another factor presented by participants was the number of *alternation* between two interfaces (2p). E.g., he faces no big problem in the period that the alternation between AZERTY and QWERTY is very frequent. The problem arises when the alternation frequency decreases and it involves larger periods.

5.2.2.5 *Strategies to avoid retroactive transfer*

To overcome retroactive interference produced by *similarity*, some often try to consciously emphasize the differentiating factors between the two interfaces (2p). The deficit caused by retroactive interference can be reduced by preparation, however they mentioned that they cannot fully avoid the interference. E.g., trying to think only in French while using AZERTY, and in English while using QWERTY.

One participant also said that alternating between similar languages on a keyboard can be generally confusing. But if the language is Chinese, she makes no errors. Since in her mind the Chinese language has fundamental differences from the latin languages. Another participant mentioned that he differentiates the way he interacts with each interface to avoid confusion; using mostly keyboard shortcuts with Windows at work and rather "point and click" style of interaction with his macOS at home.

Furthermore, one programmer reported that he tries intentionally reduce his exposure to the new interface to alleviate the impact of practice on the amount of retroactive interference. He is avoiding to write code on macOS, doing only final compatibility check of his code, so as not to be confused when returning back to his primary system (Linux). In more extreme cases, participants reduced the amount of practice to zero, sacrificing functionalities for consistency. For instance, a programmer abandoned the Visual Studio code editor while having unique useful features, to benefit from a consistent work flow, using solely the Geany code editor as it is the only one compatible across all operating systems.

5.2.2.6 *Conclusion*

Several factors involving retroactive transfer were spontaneously mentioned by participants. The reported factor by all the participants is the amount of *similarity* between two interfaces (6p). Based on a research work (Osgood, 1949), the amount of retroactive transfer is affected by similarity during switching between two tasks. The principle that appears to operate in such situations is that the greater the similarity, the greater the degree of negative transfer. The next factor influencing retroactive transfer is the *amount of practice* of the previous and new method (Lewis and Miles, 1956) which experienced by three participants. Moreover, the distribution of the amount of practice, as mentioned by the interviewees, can also have an impact on retroactive transfer (Healy et al., 2011). Therefore participants' elaborated observations appear consistent with the literature described in the previous section. Entering text on different keyboards appears to be both a frequent task and a source of retroactive interference. I thus decided to conduct another round of interviews with two additional participants focusing on keyboard layouts.

5.3 INTERVIEW 2: POST-STUDY FOCUSING ON KEYBOARD USAGE

The second round of interview focuses explicitly on keyboard usage based on the findings of the first round. As shown in the Figure 31, 35% of negative retroactive transfer's incidents occurred through typing with different keyboard layouts. In order to better understand the user behaviour and investigate the source of interference, this interview was conducted with two HCI researchers. As computer scientists they extensively use keyboards, and since they are French, they used regularly two keyboards, both AZERTY and QWERTY. The second reason that makes these interviews suitable is that we are colleague and I am familiar with the way they switch between keyboards. Lastly, as HCI researcher, they possibly have the ability to better reflect on their own usage of technology.

During the interview I was focusing on their episodic experiences from 3 weeks to 3 years in their life, when they experienced retroactive interference while using a keyboard.

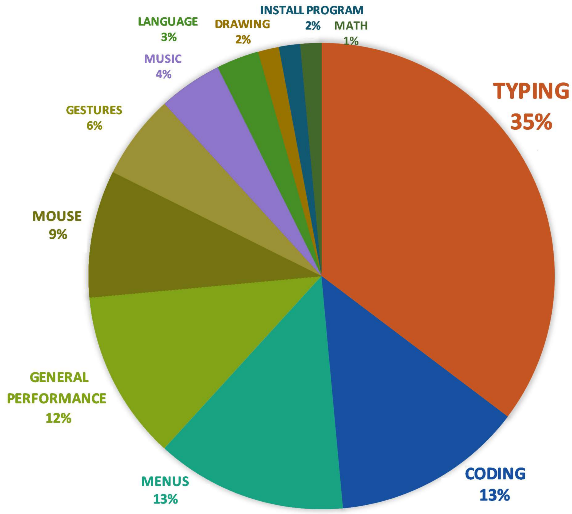

Figure 31: Based on user's experience, using a keyboard is a main source of retroactive interference.

5.3.1 *Participant*

I interviewed 2 adults (< 40 years), 2 male and French. They were HCI researchers for more than 10 years and have the experience to work with keyboard layouts for more than 20 years.

5.3.2 *Text input*

The first participant was regularly alternating between his AZERTY laptop (personal and professional usage) and a QWERTY keyboard dedicated to a professional platform for about two years. During this episode, he was looking at the keyboard using several fingers. He reported doing frequent errors especially when he knew that the consequences of an error were not important. After some time, he was able to anticipate potential sequences of characters that could lead to typing errors and voluntary slow down his typing speed to avoid them.

The second participant was using an AZERTY laptop at home, but an external QWERTY keyboard connected to this laptop at work during 3 weeks. He was able to enter text without looking at the keyboard. He reported doing errors and additional visual search for non frequent special characters. However, he reported that switching keyboards was like switching modes: *"I was doing one error but not two. I need to recall which mode I was using"*. The second participant was also using the SWIFT keyboard on his smartphone, but for some unidentified reason the system sometimes display the default IOS keyboard. The two layouts are very similar, except that '.' is closer to the return key on the iOS keyboard. He reported doing much more errors than the previous experience and did not have the impression of "switching mode". When he was asked why, he attributed this difference to the "degree of similarity" between the two interfaces.

5.3.3 *Keyboard shortcuts*

The first participant regularly uses Inkscape on macOS which is the only software using Ctrl instead of Cmd as main modifier. He reported doing *"one, max two errors"* and then being comfortable using these keyboard shortcuts. This echoes the impression of "switching mode" of the first participant when alternating keyboard layouts. He also reported that the context is so different that coming back to "normal" software is fast.

5.4 DISCUSSION AND CONCLUSION

To summarize, I discuss the main findings of this chapter in the following:

5.4.1 *What are the interview's findings?*

The complementary functionalities between two interfaces is the primary reason for people to alternate between interfaces to perform a single task. The negative impact of this alternation rises up especially at the beginning of switching, which results in a performance decrease.

5.4.2 *Necessity of investigating retroactive transfer*

All the respondents experience retroactive interference. Moreover, most of them experience retroactive interference several times. Also, the reported incidents mainly focused on *text entry* interfaces. This is surprising as the HCI literature did not focus on this phenomenon. A lot of research has been done on proactive transfer but I am not aware of work on retroactive transfer. These motivate me to further investigate retroactive transfer phenomenon, focusing on text entry.

5.4.3 *Factors*

My review of the psychology literature highlighted several factors that contribute to retroactive transfer, Chapter 4. *Similarity* and *practice* were the more commonly factors, that reported in my interview study as well. Similarity has been considered as an important criterion in the optimization of user interfaces for proactive transfer (Grudin, 1989; Kellogg, 1987).

One interesting factor is *alternations*. Indeed, this factor was not really discussed and studied in experimental study. However, the participants reported performing multiple alternations between user interfaces. This factor is especially relevant in HCI because of the ubiquitous nature of interaction.

5.4.4 *Implications*

In the following chapter, I build on these findings to design a controlled experiment. I aim to understand whether retroactive transfer occurs when interacting with user interfaces. In particular, I investigate the impact of similarity and number of alternations on user performance when entering text.

5.4.5 *conclusion*

In this chapter, I described introspection and two rounds of interviews to investigate different scenarios involving retroactive transfer phenomena. The interviews provided insights about users' experience and challenges when alternating with interactive systems. The impactful factors on retroactive transfer magnitude derived from result of interviews are the amount of practice, similarity and the number of alternation.

6 EXPERIMENT

I investigate retroactive transfer from several perspectives. I used a theoretical approach in Chapter 3 and Chapter 4 by presenting the previous work on *skill acquisition* and *transfer of skills*. They revealed several investigations of retroactive transfer phenomena in psychology, but not in HCI. This is surprising as users are frequently alternating between interfaces. In Chapter 5, I investigated retroactive transfer in HCI with *qualitative* methods confirming that users experience the negative impact of retroactive interference with interactive systems, especially in the context of text entry. In this chapter and the next chapter, I investigate retroactive transfer with *quantitative* methods. I conduct a laboratory experiment to study the main factors on a HCI task (text entry). In this chapter, I detail the experimental design to collect data. In the next chapter, I analyse the results and discuss the findings.

6.1 DESIGN RATIONALE

Our review of the psychology literature (Chapter 4) highlighted several factors that contribute to retroactive transfer, from which **similarity** and **practice** were the more commonly reported in the interview study (Chapter 5). The impact of similarity on retroactive interference was reported as task-dependent, especially in the second part of the interviews. It means similar tasks lead to impaired performance and false memories by priming other related tasks. In addition to these factors, participants reported performing repeated **alternations** between user interfaces.

This chapter presents an experiment based on the results of two rounds of interviews, that aims to deepen the understanding of retroactive transfer in interactive system. During the interviews, I exposed participants to several UI scenarios (mouses, menus, browsers, etc.). The reported incidents mainly focused on *text entry* interfaces. Thus the experimental task was constructed by abstracting a real text entry task, to operationalize several important factors.

6.1.1 *Abstraction & operationalizing*

Initially I contemplated to use a regular text entry task to study retroactive transfer phenomena. However, mastering a single key-

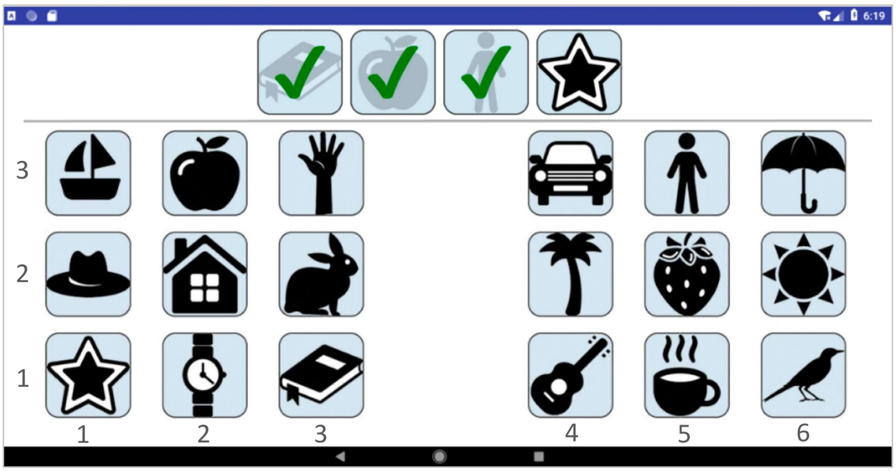

Figure 32: Interface displayed on the tablet. Four target symbols are displayed on the top. The green check marks confirm correct selections. Participants select the symbols from the grid at the bottom. Digits were not present in the interface. They serve to identify a symbol in this paper.

board layout requires a lot of time, i.e. several days, and studying retroactive transfer with two keyboard layouts and alternations would require at least 3 times that amount, which was not a feasible option for a lab experiment (~1h30). Thus I present an abstract task (Figure 32) that operationalizes the key aspects of alternating between two keyboard layouts, alleviating possible bias related to their previous experience, accelerating users' expertise and allows us to focus on transfer of skills. The proposed abstract grid layout contains fundamental structure of the real keyboard buttons and the ability of key selecting.

Abstraction of the real-world task and operationalized factors to perform a lab experiments is a standard evaluation method in HCI. Operationalization means turning abstract concepts into measurable observations. There are widely used examples in the HCI literature.

For instance, several simple and abstract variants of "Fitts' Law pointing" experiments (Fitts, 1954) have been considered in HCI. Accot and Zhai (Accot and Zhai, 1999) developed the Steering Law as an evaluation paradigm for input devices. In their experiment the participants performed two types of steering tasks with straight and circular tunnels with five different input devices. With this quantitative model, they were able to classify these devices into three categories based on statistical differences in performance.

Card et al. (Card et al., 1980) proposed the Keystroke-Level abstract model for predicting user performance time for a given task. This simple model evaluates time by counting keystrokes and other low-level operations such as the user's mental preparations and the system's responses. It has been tested with several systems and shown to be accurate and flexible enough to help practical design and evaluation.

6.1.2 *Interface design*

Now I will describe the grid layout design in more details:

Figure 32 illustrates the interface, a virtual grid layout of 3×6 common symbols (e.g. hat, rabbit, etc.) designed according to the following criteria: First, the interface captures the key phenomena of text input. The grid in Figure 32 represents an abstraction of a (virtual) keyboard layout. Selecting an element in the grid involves visual search, pointing, chunking, learning and motor control. The two-sided layout further allows for multi-finger and two-handed interaction, see Figure 33. Consequently, the abstracted grid acts as an informative proxy for a wider class of interfaces such as numpads or grid menus.

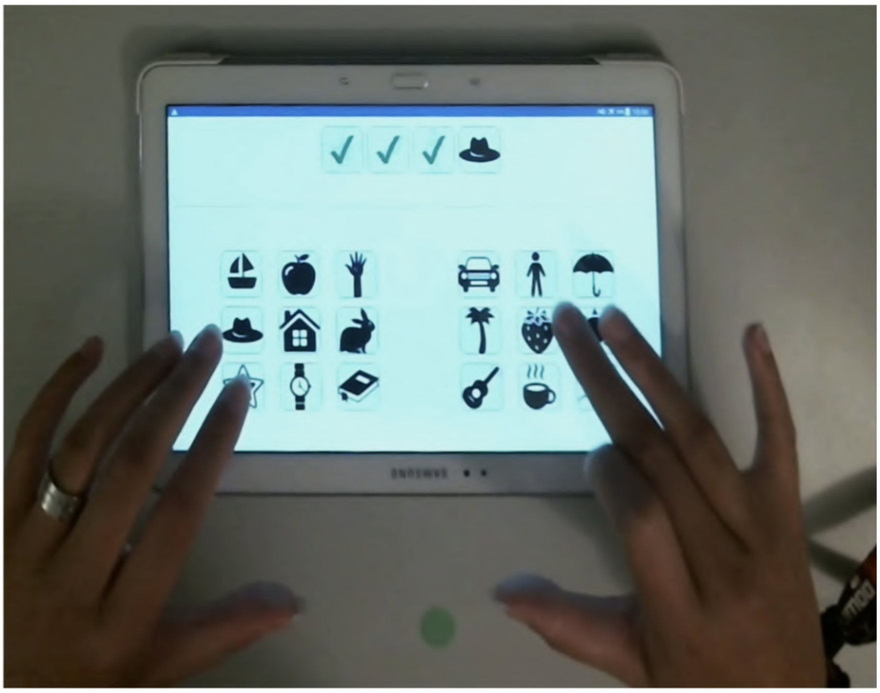

Figure 33: experimental setup. The sequence of four target symbols is displayed at the top of the interface. A user selects the corresponding symbols by touching the grid at the bottom. Selecting an element in the grid layout involves visual search, pointing and motor control.

Second, the interface fosters rapid skill acquisition within the time constraints of the experiment. While the number of rows (3) was similar to keyboard layouts, I used 6 instead of 10 columns to enable participants to reach a performance plateau. The advantage of the simplified grid over a real keyboard is that it can reduce visual search time and simplify finger-key assignation, both contributing to touch typing skills.

Third, I wanted to prevent confounding factors from prior user experience. Therefore, I replaced letters with symbols to ensure that the chosen interface would not remind users of existing keyboard layouts to avoid unintended skill transfer.

Finally, I wanted to isolate mapping-related errors from retroactive interference. Thus I increased slightly the size of the buttons from 0.6 to 0.9 inches to reduce irrelevant pointing errors due to the fat finger problem (Siek et al., 2005).

In summary, I developed an abstracted layout to study retroactive transfer within an interactive system. If I were to use real keyboards, I would probably face differences in skill level with the chosen keyboards among participants. The nature of the keyboard layouts and the frequency of the letters would also introduce additional factors difficult to disentangle. It is likely that the targeted phenomenon will be more difficult to observe and/or to explain. This interface maintained the key aspect of text input while remaining flexible enough to control the design factors described below.

6.2 OBJECTIVE

The primary goal of this experiment was to understand the retroactive interference phenomena and how learning a **N**ew layout (N) interferes with the retention of a **P**reviously learned layout (P), as described in the sequence below:

$$P \rightarrow N \rightarrow \boxed{P} \tag{10}$$

First, I investigated the impact of the *similarity* on retroactive transfer. The degree of similarity has been manipulated between N and P by modifying the location of certain elements in the layout. I controlled both the *number of changes* between the two layouts as well as the *spatial proximity* of these changes (i.e. how far an element has been moved).

Second, I investigated the impact of *alternation* on retroactive transfer. So I tested two alternations rather than the typical one alternation by extending the learning sequence:

$$P \rightarrow N \rightarrow P \rightarrow N \rightarrow \boxed{P} \tag{11}$$

Where participants alternate two times between the layouts P and N before measuring the performance with the layout P.

In this chapter, I thus answer the following research questions:

- What is the impact of alternations on the performance?
- What is the impact of similarity between the layouts on the performance?

6.3 experimental materials

All experimental materials are available on OSF.

The Open Science Framework (OSF) is a tool that promotes open, centralized workflows by enabling capture of different aspects and products of the research lifecycle, including developing a research idea, designing a study, storing and analyzing collected data, and writing and publishing reports or papers. It is developed and maintained by the Center for Open Science (COS), a nonprofit organization founded in 2013 that conducts research into scientific practice, builds and supports scientific research communities, and develops research tools and infrastructure to enable managing and archiving research (Foster and Deardorff, 2017).

6.4 participants

58 university engineers and students aged 18-40 participated to the experiment and were divided into three groups, one group per condition (see below). 4 participants were removed due to under-performance during the training phase to fairly ensure similar initial performance across conditions. It results that each condition was tested with 18 participants. The exclusion rule was decided before running the statistical analysis to prevent p-hacking (Head et al., 2015; Wicherts et al., 2016). Participants received 15 euros for their participation. A bonus of 10 euros was awarded to the 3 fastest participants of each condition to motivate them to quickly reach a high level of performance.

6.5 apparatus

I used a Galaxy Note multi-touch tablet on Android 5.1. The display was 10.1 inches with a resolution of 2560x1600 pixels. The tablet was lying on a table with the landscape orientation. Participants sat on a chair and were free to move the tablet on the table to have a high level of comfort (Figure 33).

6.6 EXPERIMENTAL DESIGN

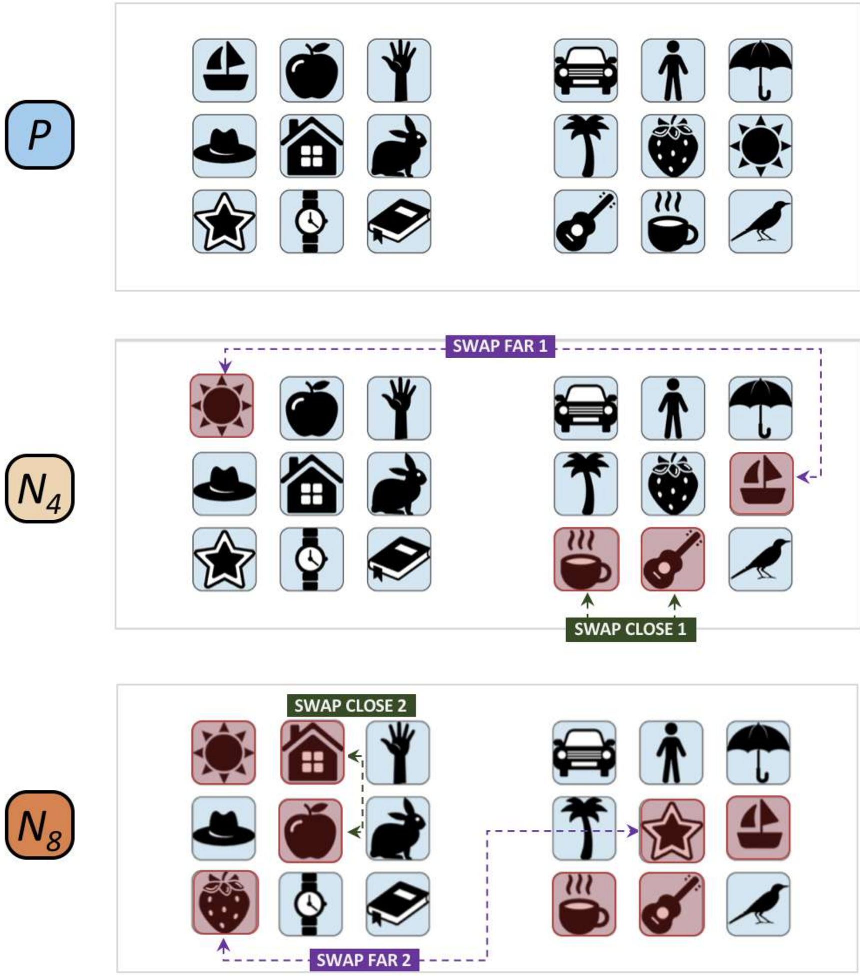

Figure 34: For controlling the similarity, I have a control layout P as previously learned interface. To study the impact of similarity on retroactive transfer, two new layouts was designed that differed from the layout P. The layout N_4 is identical to layout P except two pairs of symbols which are swapped, one is far and one is close to control the proximity. The new layout N_8 is identical to N_4 except two more pairs of symbols which are swapped.

6.6.1 *Task and stimulus*

A sequence of four target symbols was displayed at the top of the interface (Figure 32). Participants selected the corresponding symbols by touching the grid at the bottom. When the target symbol was *correctly* selected, a green check mark confirmed the

a	*Phase*	1 → 2 → 3 → 4 → 5
b	*Alternation Sequence*	P → N → P → N → P
c	*Condition control*	P → ∅ → P → ∅ → P
d	*Condition 4-change*	P → N_4 → P → N_4 → P
e	*Condition 8-change*	P → N_8 → P → N_8 → P
f	*Practice Time (min)*	10 → 10 → 10 → 10 → 10

Table 5: Summary of phases, alternations, conditions and practice time for each condition. Blue colors indicate the layout P and orange colors the layout N. (a) Phase: an index of exposure to the layouts. (b) Alternation Sequence: the order of appearance of the layouts. (c, d, e) the conditions determined the number of changes between layouts P and N. (f) Practice time for each phase.

selection and participants proceeded to the next target in the sequence. When an *error* was made, a beep informed participants to re-select the symbol. Once the sequence was successfully completed, a novel sequence was displayed.

6.6.2 *Procedure and phases*

Participants filled out a consent form and turned off all personal devices. The experimenter explained the task and asked participants to complete it as quickly as possible. The experimenter encouraged the participants to use both hands and several fingers to maximize their performance. Table 5a shows the 5 phases (1 2 3 4 5) of the experiment. Each phase lasted about 10 min. Between phases there was minimum 1 minute break. During the phases 1 , 3 and 5, all participants selected symbols using the layout P (the selection task was detailed in the section *Task*). During the phases 2 and 4, the participants of the condition control took a break (10+1 min), while the participants of the two other conditions selected symbols using the layout N. The configuration of the layout P is illustrated in Figure 32. The layout N differs depending on the condition (condition 4-change or condition 8-change). I next describe the design of the layout N.

6.6.3 *Layout N and similarity*

The layout N was used in the phases 2 and 4. To study the impact of similarity on retroactive transfer, the layout N differed from the layout P in two components of similarity (as shown in the Figure 34 N_4 and N_8):

6.6.3.1 *Number of changes*

Our primary measure of similarity and dissimilarity was the number of paired symbols swapped between the layouts. More precisely, the layouts N and P were identical in geometry (3×6 cells) and in list of symbols. The dissimilarity between N and P was determined by the minimum number of (swap) operations needed to transform the layout N into the layout P. Thus the layouts N and P differed only on the location of swapped symbols.

6.6.3.2 *Proximity*

The number of changes alone does not capture the *nature* of the changes. I thus introduced a second similarity measure termed *proximity*. Proximity indicated the number of cells that existed between the previous and the new location of a symbol. Consider a keyboard layout; swapping either two adjacent keys or two keys far from each other might affect user strategies and the risk of errors. I considered two proximity conditions (Figure 35):

- *Close*. The two locations are adjacent.
- *Far*. There are at least 5 cells between the two locations. Consequently, the previous and the new location of the symbol are in different sides of the grid.

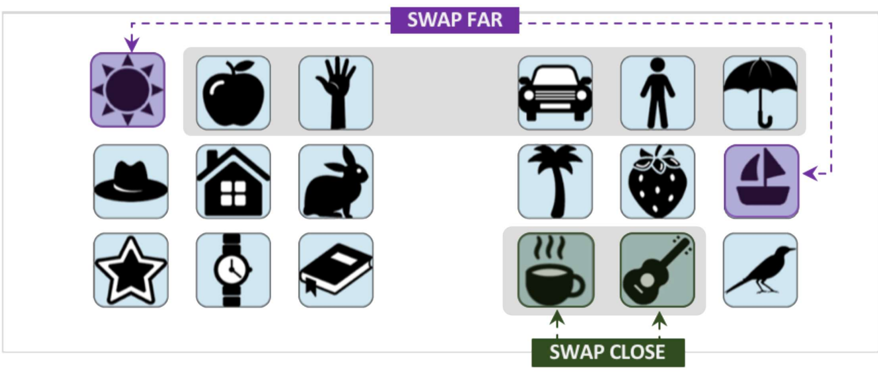

Figure 35: Close and far proximity between previous and new location of a symbol.

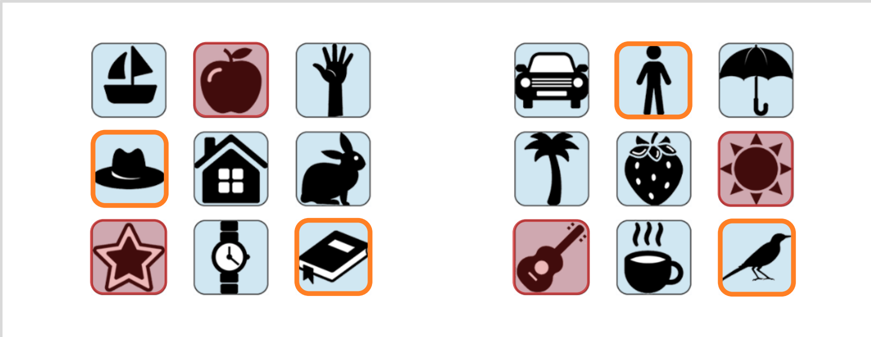

Figure 36: Targets in orange borders illustrate the static target symbols and the red targets illustrate the dynamic targets used in this experiment.

6.6.3.3 *Configuring the layout* N

In accordance with the similarity measures, I designed two layouts N: N_4 and N_8. In condition 4-change, participants used the layout N_4 as interference layout, and in condition 8-change, the layout N_8.

Specifically, the *layout* N_4 was identical to P except 2 pairs of symbols which were swapped. Swapping means 4 symbols changed location and 14 symbols remained at the same location in the grid. Among the two swaps, one was close and one was far to control the proximity. The layout N_8 was identical to N_4 except 2 (extra) pairs of symbols which were swapped. Among the 2 swaps, one was close and one was far. Comparing N_8 to P, 4 pairs of symbols were swapped (i.e. 8 symbols changed location) containing 2 close and 2 far swaps. In summary, layout N_4 in comparison with layout N_8 was more similar to layout P, because N_4 had fewer number of changes (i.e. only 4 symbols), but for designing the layout N_8, 8 symbols of layout P have been changed. Thus by comparing the performance of the 4-change condition (using N_4) and 8-change condition (using N_4), I tested the impact of *similarity* on retroactive interference.

6.6.4 *Target symbols: static and dynamic*

From the 18 (3×6) symbols of each layout, participants had to select 8 of them. Table 6 shows these 8 target symbols. Figure 36 illustrates the static targets symbols in orange borders and illustrates the dynamic targets in red color. I distinguish between *static* and *dynamic* targets. Static targets had identical locations in all layouts (P, N_4 and N_8). Dynamic targets had changed locations be-

				Location		
				Previous	*New*	
	Prox.	No.	Icon	control	4-change	8-change
Static	Fix	1		(1,3)	(1,3)	(1,3)
		2		(3,5)	(3,5)	(3,5)
		3		(2,1)	(2,1)	(2,1)
		4		(1,6)	(1,6)	(1,6)
Dynamic	Close	1		(1,4)	(1,5)	(1,5)
		2		(3,2)	(3,2)	(2,2)
	Far	3		(2,6)	(3,1)	(3,1)
		4		(1,1)	(1,1)	(2,5)

Table 6: Target symbols' locations (as shown in Figure 32) for the three layouts. These targets are divided into two types: static and dynamic.

tween the layout P and the layouts N_4 and/or N_8. The reason for asking participants to also select static targets was to understand whether changing the location of the learned symbols (dynamic) can influence the performance of the unchanged symbols (static).

To be able to compare the performance of static and dynamic targets, the locations of the static symbols vertically mirrored the locations of dynamic symbols (i.e., mirrored in Figure 32). To measure the effect of proximity, half of the dynamic targets were involved in a close change and half in a far change.

6.6.5 *Design*

The experiment had a mixed design. As seen in Figure 37 The participants of condition control (Table 5c) learned only the layout P performing phases (1, 3, 5). The participants of condition 4-change (Table 5d) learned both layouts P and N_4 performing all phases (1,2,3,4,5). The participants of condition 8-change (Table 5e) learned both layouts P and N_8 performing also all phases. Each phase contained 9 blocks. Each block contained 16 trials. In each trial, participants selected 4 target symbols (a total of 64 selections per block). The 8 target symbols appeared randomly within the block following a uniform distribution similar to (Altmann and Gray, 2008).

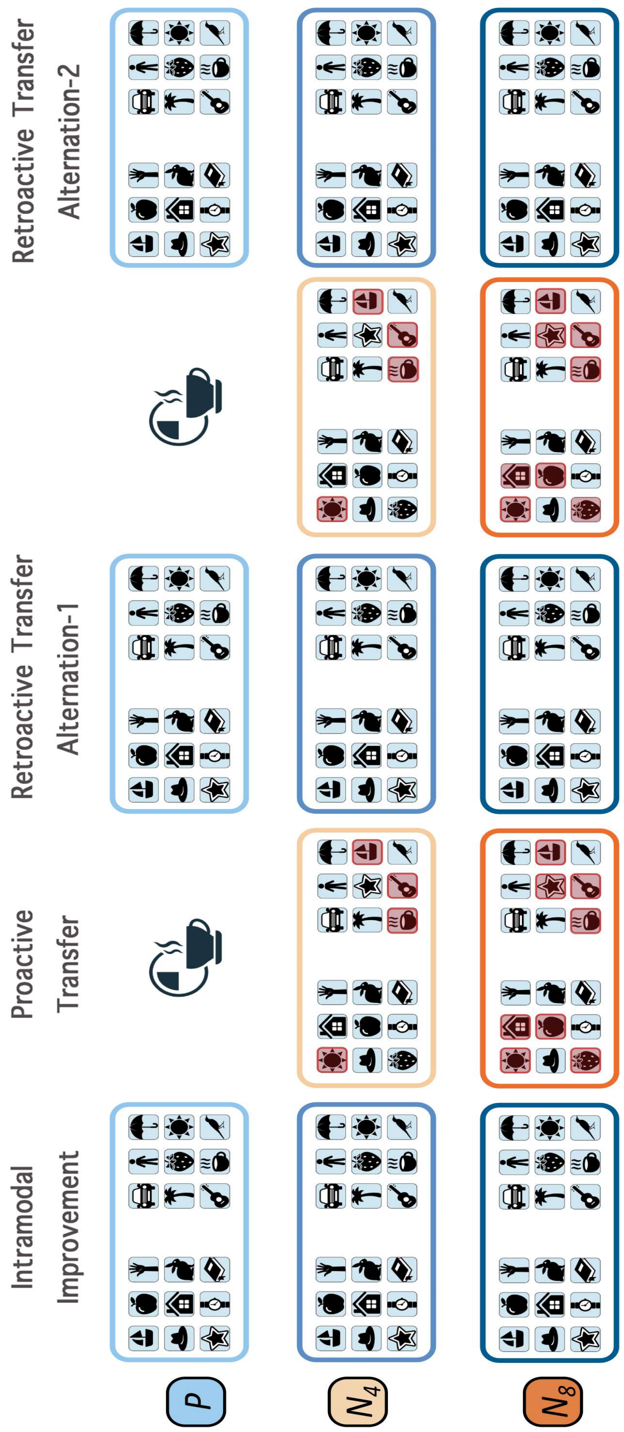

Figure 37: In overall there are three conditions, the control condition, in which the users learned only the layout P, and had the rest-time in between. The users of condition N_4 learned both layouts P and N_4 and the users of condition N_8 learned both layouts P and N_8.

In summary, the design was: 3 conditions × 18 participants × 5 phases (only 3 phases for the condition 1)× 9 blocks × 16 trials × 4 targets = 134 784 selections.

6.7 DATA INTERPRETATION

6.7.1 *Independent variables*

I considered five independent variables. The between factor was:

- CONDITION (control, 4-change and 8-change) indicating the number of changes.

The within factors were:

- TYPE (static and dynamic)
- PROXIMITY (close and far)
- ALTERNATION (1, 2) Alternation-1 occurred in phase 3 and alternation-2 in phase 5.
- BLOCK (1-9)

6.7.2 *Dependent variables*

Retroactive transfer is analysed concerning the first and second alternation. Dependent variables for each of them is as follow:

6.7.2.1 *Retroactive transfer, Alternation-1*

(Figure 18c): To investigate the effect of learning a new layout (first exposure to layout N) on the performance of the layout P, I measured the *temporal performance drop* between phases 1 and 3 (Yotsumoto et al., 2013).

6.7.2.2 *Retroactive transfer, Alternation-2*

(Figure 18d): To investigate the effect of alternation (second exposure to layout N) on the performance of layout P, I compared the *temporal performance drop* between phases 1 and 3 with the *temporal performance drop* between phases 3 and 5 .

I also measured *error* per block, i.e. The number of incorrect attempts to select a target for these phenomena.

6.7.3 *Statistics*

To be consistent with previous retroactive transfer studies, I analyzed the data using two-way mixed anova (Healy et al., 2011). To better communicate the findings (Dragicevic, 2016), I conducted a second analysis of the same data using 95% confidence intervals (CI), which I report visually in Figure 40. The results with both methods were consistent.

6.8 conclusion

In this chapter, I described an experimental design to investigate retroactive transfer phenomena while alternating between two abstract grid layouts. The experimental task and the controlled factors are inspired by the result of two interviews and based on real experiences of the users, Chapter 5. Instead of using the real keyboard, an abstract grid layouts was used. It eliminates the cognitive aspects of learning a new complex keyboard and focuses on the transfer level, so that the drop of performance after a retroactive transfer can be measured and compared across experimental conditions. The task is controllable with several impactful factors (i.e., the amount of similarity, practice time and number of alternation) on amplitude of interference, thus allowing to quantitatively compare the results and user behaviors while performing the experiment.

I will describe the results of this experiment in the following chapter and explain four parts of the experiment: intramodal improvement, proactive transfer, retroactive transfer in first alternation and retroactive transfer in second alternation.

Part III

DATA ANALYSIS

7

STATISTICAL RESULTS

As explained in previous chapter, a controlled lab experiment has been run to investigate the influence of retroactive transfer phenomena on user's performance. This chapter describes the data analysis of the study presented in the previous chapter (Chapter 6) to uncover the effects of retroactive interference. It also present the result concerning other learning phenomena related to the retroactive transfer, intramodal improvement and proactive transfer. In overall the analysis focused on four phenomena: intramodal improvement, proactive transfer and retroactive transfer for first and second alternations.

More precisely, each phenomena had its own dependent variables. *Intramodal Improvement* (Figure 18a) and the effect of practice on learning process of P in phase 1, has been measured using the average *selection time* per block. *Proactive transfer* has been measured by the *temporal performance drop* between phase 1 and phase 2. It shows the effect of learning a previously learned layout P on the performance of the layout N. This measurement is based on reviewed previous works in Chapter 4. It is defined as the difference of average selection time between the end of phase 1 (last block [1]) and the beginning of phase 2 (first block) (Schmidt and Lee, 1988; Singley and Anderson, 1989).

Retroactive transfer, alternation_1 (Figure 18c) has been measured by the ***T****emporal* ***P****erformance* ***D****rop* (TPD) between phases 1 and 3 (Yotsumoto et al., 2013). This measurement gives the effect of learning a new layout (first exposure to layout N) on the performance of the layout P. Finally to investigate *Retroactive transfer, alternation_2* (Figure 18d), I compared the *temporal performance drop* between phases 1 and 3 with the *temporal performance drop* between phases 3 and 5. The result shows the effect of alternation (second exposure to layout N) on the performance of layout P. I analyze these dependent variables regarding the following independent variables:

- CONDITION (control, 4-change and 8-change) which indicates the number of changes

[1] I also considered the best block (instead of the last block) for proactive and retroactive transfer. I considered the best block as some participants could experience fatigue at the end of each block. However, the results were consistent for both analysis (last block vs. best block). I thus decided to only report data for the last block.

- TYPE (static and dynamic)
- PROXIMITY (close and far)
- BLOCK (1 TO 9)
- ALTERNATION (1 and 2) in which alternation_1 occurred in phase 3 and alternation_2 in phase 5

Condition is the only between factor, and the rest of variables are within factors. ANOVA and confidence intervals are the methods I used to make a link between these independent and dependent variables.

7.1 METHODOLOGY

7.1.1 *Analysis of variance*

In this chapter, I use Two-way mixed ANOVA as a main method. Analysis of variance (ANOVA) was devised originally to test the differences between several different groups of treatments (Snedecor and Cochran, 1980). ANOVA is a method of great complexity and subtlety with many different variations, each of which applies in a particular experimental context. Two-way analysis of variance (ANOVA) examines the influence of two different independent variables on one continuous dependent variable. The two-way ANOVA not only aims at assessing the main effect of each independent variable but also if there is any interaction between them (Fujikoshi, 1993).

7.1.2 *Confidence interval*

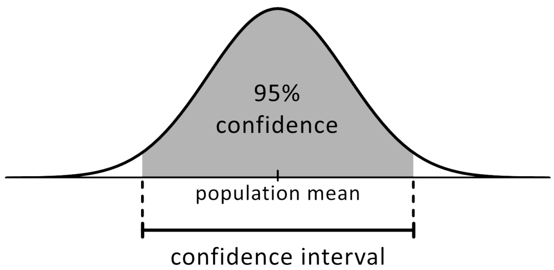

Figure 38: Distribution of sample means around population mean.

In all plots, error bars show the 95% **C**onfidence **I**nterval (CI). CI is a type of estimate computed from the statistics of the observed data. It indicates that the true population mean probably lies based upon a much smaller random sample taken from that population (Smithson, 2002). In statistical analysis, most commonly a 95% confidence level is used (Zar, 1999). A 95% Confidence Interval of a Mean (Figure 38) is the interval that has a 95% chance of containing the true population mean.

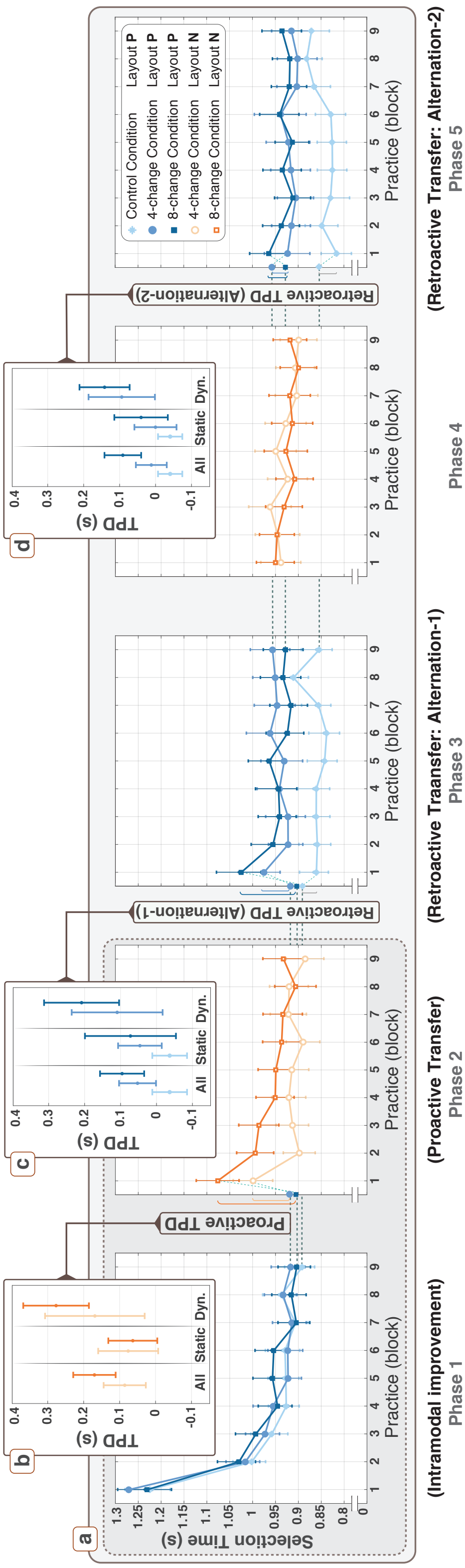

Figure 39: (a) Intramodal improvement (time) of layout P for all phases per BLOCK × CONDITION for all targets. (b) Proactive Transfer. (c) Retroactive Transfer in alternation_1. (d) Retroactive Transfer in alternation_2. (mean TPD per CONDITION (number of changes) × TYPE OF TARGETS (static vs. non-static) was calculated for b,c,d). Error bars indicate 95% CI.

Figure 40 compares the learning curves for the conditions control, 4-change and 8-change. Blue colors indicate the analysis of the layout P and orange colors the analysis of the layout N. I report both analyses (TWO-WAY MIXED ANOVA and CI) on intramodal improvement (a), proactive transfer (b), and retroactive transfer for alternation_1 (c) and alternation_2 (d). I only report selection time and *mean* temporal performance drop among participants (TPD) along with CI, as I did not find effects of the different factors on ERROR.

7.2 INTRAMODAL IMPROVEMENT

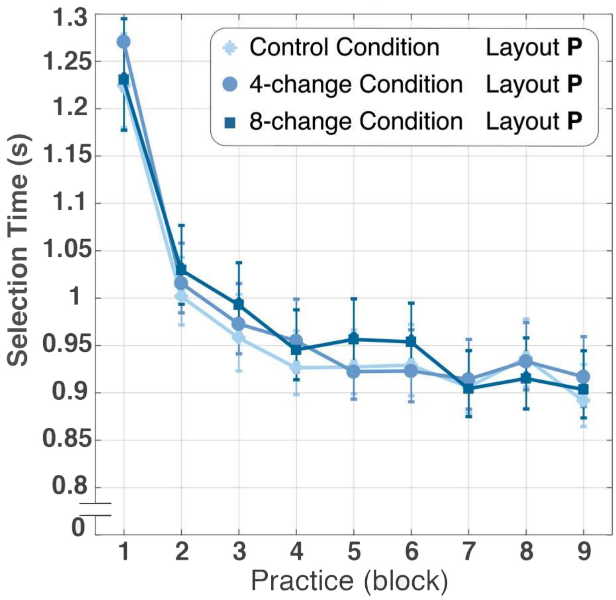

Figure 40: (a) Intramodal improvement (time) of layout P for all phases per BLOCK × CONDITION for all targets. Error bars indicate 95% CI.

To measure intramodal improvement, I analyzed all blocks of phase 1 for all conditions. A CONDITION (control, 4-change, 8-change) × BLOCK (1-9) ANOVA was performed on TIME with a repeated measures analysis of the last factor. It yielded a significant effect of BLOCK, $F_{8,408} = 83.68, p < 0.0001$. Post-hoc comparisons with Tukey HSD test indicated that participants saved 300ms (25% improvement) from block 1 to block 4 and no significant differences from block 4 to 9. It indicates that participants reached a plateau of performance with the layout P. I did not observe an effect of CONDITION. **As all participants used the same layout P, it confirms similar initial performance across conditions.** The

CI analysis, illustrated in Figure 40a, also shows no observable difference in performance among the participants of the different conditions.

7.3 PROACTIVE TRANSFER

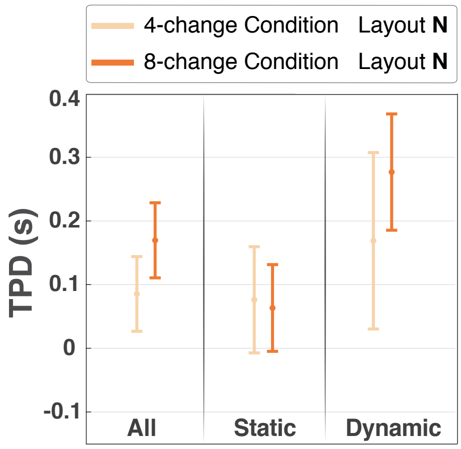

Figure 41: Proactive transfer. Mean temporal performance drop (TPD) per CONDITION (number of changes) × TYPE OF TARGETS (static vs. non-static) was calculated. Error bars indicate 95% CI.

Proactive transfer has been measured by the *temporal performance drop* (TPD) to show the difference of average selection time between the end of phase 1 (last block 1) and the beginning of phase 2 (first block).

7.3.1 *All targets*

I first compared the two conditions 4-change and 8-change considering *all targets*. ANOVA revealed a significant effect of CONDITION on TPD, $F_{1,34} = 4.48, p < 0.05$. A post-hoc Tukey HSD test shows that TPD with N4 (+86 ± 59ms) is significantly smaller than the one with N8 (+170 ± 59ms), suggesting that the TPD increases with the number of changes. The CI analysis, illustrated in Figure 41 (All targets), confirms a difference between the two conditions and that both conditions are affected by a performance drop (0 is not included in the CI).

7.3.2 *Static vs. dynamic targets*

I then refined the analysis by distinguishing *static vs. dynamic* targets (see the list of static and dynamic targets in both layouts

N_4 and N_8 in Table 6). I conducted a CONDITION (4-change, 8-change)×TYPE (static, dynamic) ANOVA with a repeated measures analysis of the last factor.

It yielded a significant effect of TYPE on TPD ($F_{1,34} = 7.86, p < 0.01$). A post-hoc Tukey HSD test shows the TPD caused by static targets (+70 ± 53ms) is significantly smaller than the one caused by dynamic targets (+240 ± 76ms). However, I did not have an effect of CONDITION on TPD ($p = 0.3$) or CONDITION×TYPE interaction effect (p = 0.2). **It suggests that the larger performance drop of N_8 is due to the extra number of changes. However this extra number of changes does not affect the tpd of the other static and dynamic targets.**

7.3.3 *Proximity*

Finally, I refined again the analysis to study the impact of PROXIMITY on the TPD of dynamic targets. I conducted a CONDITION (4-change, 8-change)×PROXIMITY (close, far) ANOVA with a repeated measures analysis of the last factor. ANOVA revealed no effect of CONDITION ($p = 0.1$), PROXIMITY ($p = 0.7$) or their interaction ($p = 0.7$) on TPD.

7.4 RETROACTIVE TRANSFER: ALTERNATION_1

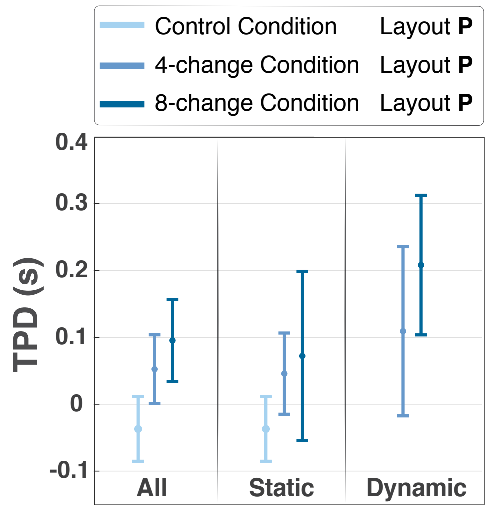

Figure 42: Retroactive transfer, alternation_1. Mean temporal performance drop (TPD) per CONDITION (number of changes) × TYPE OF TARGETS (static vs. non-static) was calculated. Error bars indicate 95% CI.

Retroactive transfer, alternation_1 has been measured by the temporal performance drop (TPD) between phases 1 and 3. This measurement gives the effect of learning a new layout N on the performance of the layout P.

7.4.1 *All targets*

I first compared the three conditions (control, 4-change and 8-change) and considered all targets . ANOVA yielded a significant effect of CONDITION on TPD, $F_{2,51} = 6.8, p < 0.005$. Post-hoc comparisons using Tukey HSD test indicated that condition control (-37 ± 48ms) has a significant smaller TPD than condition 4-change (+52 ± 51ms) and condition 8-change (+95 ± 61ms). But there was no significant difference between the conditions 4-change and 8-change. The CI analysis, illustrated in Figure 42 (All targets), confirms a difference between the conditions and that conditions 4-change and 8-change are affected by a performance drop (0 is not included in the CI).

I next refined the analysis by investigating static and dynamic targets. As condition control does not have dynamic targets, I first performed an analysis focusing only on static targets for all conditions.

I then excluded the condition control and compared static vs. dynamic targets by considering only conditions 4-change and 8-change. (similar to the analysis of proactive transfer).

7.4.2 *Static targets for all conditions*

I run a CONDITION (control, 4-change, 8-change) ANOVA which showed no significant effect of CONDITION on TPD ($p = 0.3$). The average TPD for static target is -37 ± 48ms in condition control, +45 ± 60ms in condition 4-change and +72 ± 126ms in condition 8-change.

7.4.3 *Static vs. dynamic targets (conditions N_4 and N_8)*

I conducted a CONDITION (4-change, 8-change)×TYPE (static, dynamic) ANOVA with a repeated measures analysis of the last factor. It showed a significant effect of TYPE on TPD ($F_{1,34} = 5.2, p < 0.05$). A post-hoc Tukey HSD test shows the TPD caused by static targets (+59 ± 69ms) is significantly smaller than the one caused by dynamic targets (+174 ± 81ms). However, an effect of CONDITION on TPD ($p = 0.2$) or CONDITION×TYPE interaction effect ($p = 0.6$) was not observed. **It suggests that the larger performance drop of N_8 is due to the extra number of changes. However this**

extra number of changes does not affect the tpd of the other static and dynamic targets.

7.4.4 *proximity*

Finally, I studied the impact of PROXIMITY on TPD of dynamic targets. I run a CONDITION (4-change, 8-change)×PROXIMITY (close, far) ANOVA. It showed no effect of CONDITION ($p = 0.1$), PROXIMITY ($p = 0.2$) or their interaction ($p = 0.5$) on TPD.

7.5 SECOND RETROACTIVE TRANSFER: ALTERNATION_2

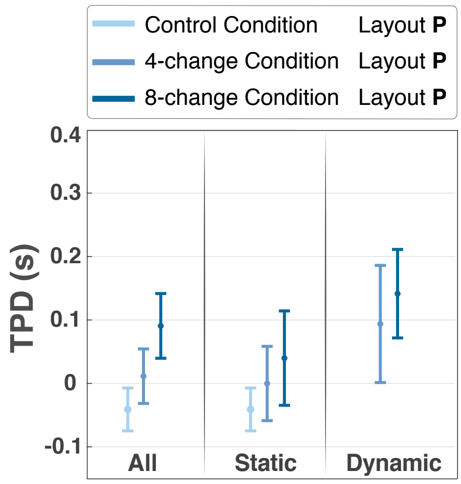

Figure 43: Retroactive transfer, alternation_2. Mean temporal performance drop (TPD) per CONDITION (number of changes) × TYPE OF TARGETS (static vs. non-static) was calculated. Error bars indicate 95% CI.

Retroactive transfer, alternation_2 has been measured by the temporal performance drop (TPD) between phases 1 and 3 with the TPD between phases 3 and 5. The result shows the effect of alternation (second exposure to layout N) on the performance of layout P.

7.5.1 *All targets*

I considered all targets and performed a CONDITION (control, 4-change, 8-change)×ALTERNATION (1,2) ANOVA on TPD with a repeated measures analysis of the last factor. It yielded a significant effect of CONDITION, $F_{2,51} = 11.56, p < 0.0001$ and ALTERNATION, $F_{1,51} = 6.35, p < 0.05$ on TPD. Post-hoc comparisons using Tukey

HSD test revealed that condition 8-change (+91 ± 51ms) has a significant larger TPD than conditions control (-41 ± 34ms) and 4-change (+12 ± 43ms), confirmed by the CI analysis in Figure 43 (All targets). Moreover, Post-hoc comparisons using Tukey HSD test shows that TPD during the alternation_1 (+52 ± 36ms) was significantly higher than the one during alternation_2 (-11 ± 34ms).

Similar to the previous subsection, I refined the analysis comparing static targets for all conditions and comparing static vs. dynamic targets for conditions 4-change and 8-change.

7.5.2 *Static targets for all condition*

I conducted a CONDITION (control, 4-change, 8-change) × ALTERNATION (1,2) ANOVA which showed no significant effect of CONDITION ($p = 0.09$) or ALTERNATION ($p = 0.1$) on TPD. The average TPD for static target is -41 ± 33ms in condition control, 0 ± 58ms in condition 4-change and +40 ± 74ms for condition 8-change.

7.5.3 *Static vs. dynamic targets (conditions N_4 and N_8)*

I conducted a CONDITION (4-change, 8-change) × TYPE (static, dynamic) × ALTERNATION (1,2) ANOVA with a repeated measures analysis of the last factor. It revealed a significant effect of TYPE ($F_{1,34} = 10.16, p < 0.005$), as well as a significant effect of ALTERNATION on TPD ($F_{1,34} = 4.97, p < 0.05$) on TPD. A post-hoc Tukey HSD test shows the TPD caused by static targets (+20 ± 47ms) is significantly smaller than the one caused by dynamic targets (+126 ± 55ms). **It also shows tpd for alternation_1 (+108 ± 52ms) is significantly higher than alternation_2 (+22 ± 49ms).**

7.5.4 *Proximity*

In another ANOVA I investigated the effect of PROXIMITY on the TPD of dynamic targets. There was no significant effect of CONDITION ($p = 0.3$), PROXIMITY ($p = 0.07$), ALTERNATION ($p = 0.1$), or of their interactions, on TPD.

7.6 ANOTHER PERSPECTIVE ON DATA

Figure 40 illustrates the comparison of conditions but Figure 44 illustrates the comparison of phases offering another perspective on the same dataset. Figure 44 compares the performance improvement for each phase given a condition. It illustrates that at the end of each phase, the selection time is similar regardless the

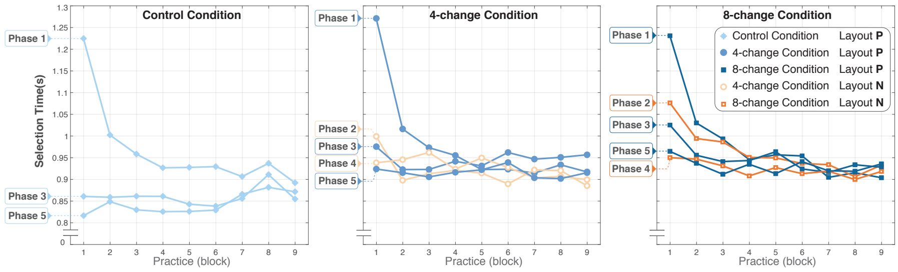

Figure 44: Intramodal improvement (selection time) for each phase for each condition.

phase indicating that users reached a plateau of performance. It also shows the initial selection time (block 0) decreases with the number of alternations but increases with the number of changes.

7.7 SELF ESTIMATION OF TEMPORAL PERFORMANCE DROP

At the end of the experiment, participants of conditions 4-change and 8-change rated the evolution of their performance for proactive and retroactive transfer (7-Likert scale). Participants reported a TPD for both proactive and retroactive transfer, which increased with the number of changes in the new layouts (Figure 45). Therefore, participants subjective performance appeared consistent with the objective metrics. However, especially for 4-change, I note that about 33.34% participants reported the impression to improve their performance when returned to the layout P.

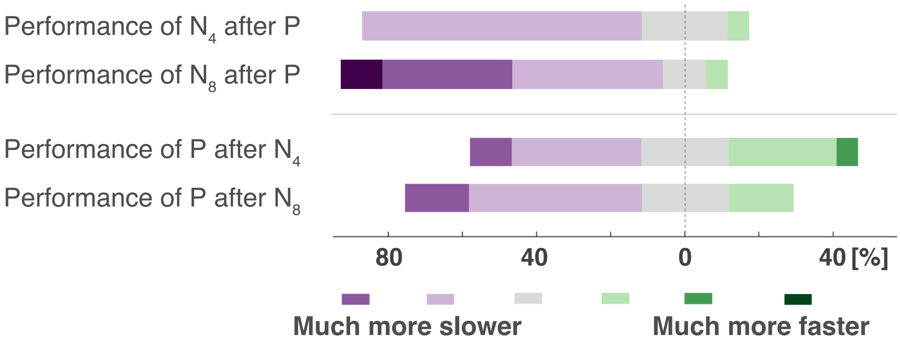

Figure 45: Participants' self estimation of their temporal performance drop (TPD) per TRANSFER (proactive - Top and retroactive - Bottom) and CONDITION (4-change vs. 8-change).

7.8 DISCUSSION

The findings of the results are as following:

R1: What is the impact of alternations on the performance?
The primary objective of this chapter was to investigate the effect of learning a new layout N on the performance of previously learned layout P. The results show that retroactive interference occurs when participants are temporally exposed to a partially changed layout (i.e. N4 or N8). The performance drop is +52ms for condition 4-change and +95ms for condition 8-change which represents 16% and 37%, respectively. I was expecting some interference, but these results remain surprising, especially for N4. Indeed, given the experimental design, 6 out of 8 targets (75%) are at the same location in P and N4. So, for 75% of the targets, users should benefit practicing N4 as it should be equivalent to continue practicing P. However, having just the two targets with different positions in N4 were sufficient to produce a significant performance drop for the *entire* interface. In other words, even a few changes in the interference interface results in retroactive interference which significantly impairs the overall performance with the previously learned interface.

R2: What is the impact of similarity between the layouts on the performance?
The ANOVA did not indicate a difference in temporal performance drop (TPD) between conditions 4-change and 8-change at either the layout level (condition) or the target level (static vs. dynamic). A key feature of the experimental design was to control two aspects of similarity: number of changes and proximity. However, neither revealed an effect on TPD. However, CI-based analysis (Figure 42) at both the layout (-all targets) and target (-static, -dynamic) levels suggest that TPD increases linearly with the dissimilarity between P and N (i.e. N8 is less similar than N4 to P). One possible explanation is that the effect exists but somehow was not captured by the experimental design or analysis. Further investigation should consider larger sample sizes, conditions with a larger number of changes and potentially more training with both P and the interference layout.

Our study aimed to evaluate users' behaviour when alternating between interfaces. The results show that the TPD significantly decreases (31%) with the number of alternations. Figure 40a illustrates this clearly with a continual decrease in the initial selection time for each phase. It suggests that retroactive interference can be reduced with alternations and practice.

Error
Contrary to expectations, I did not find a significant effect on ERROR for the different factors. One possible explanation is that the task was cognitively demanding. In more realistic scenarios, users might focus on higher level tasks (e.g. writing an email) decreasing their attention to the keyboard. I foresee that the TPD would then translate into more errors in more ecological settings, but more investigation is necessary.

Proactive vs. retroactive interference
Most results about retroactive interference are in line with proactive interference such as the effect of TYPE (static vs. dynamic) on TPD, the lack of effect of proximity and also experiencing a TPD with both conditions 4-change and 8-change by users. It confirms that switching from one interface to another one ($P \rightarrow N$ or $N \rightarrow P$) produces interference. However, for proactive interference, the condition 4-change appeared significantly less affected by the TPD than the condition 8-change, probably because its larger effect size.

7.9 CONCLUSION

To summarize this chapter, I analysed different phenomena related to retroactive interference while alternating between two layouts. The results show that having a small changes in the key' positions of interference interface is sufficient to produce a significant performance drop for the entire interface. However, increasing the number of alternation facilitates the transfer and decreases the amount of performance drop. Furthermore, the results do not show evidence of the performance drop incurred by similarity between the previous and new learned layouts. The analysis could not possibly provide insight about similarity since larger sample sizes are needed or even the effect could not captured by ANOVA analysis.

Part IV

GENERAL DISCUSSION AND CONCLUSION

8 CONCLUSIONS

8.1 SUMMARY

Given the ubiquitous nature of interaction, it is common to use different devices (keyboard layout), operating systems (Windows, Mac) or software (text editors) to achieve a single task. In this thesis, I investigated retroactive transfer phenomena while alternating between interfaces. Retroactive transfer is the influence of a newly learned interface on the performance of a previously learned interface. Based on interview findings (Chapter 5), negative retroactive transfer appears more likely to occur when alternating keyboard layouts than other interfaces. Therefore, I conducted an experiment (Chapter 6) investigating retroactive transfer between two abstract keyboard layouts. I controlled the degree of similarity between the keyboard layouts as theories in Chapter 4 suggest that similarity is an impactful factors on retroactive transfer. It is also a relevant factor to HCI as designers can more easily manipulate it. A key aspect of the experiment is to study retroactive transfer not only for the first alternation, but also for the second alternation. One of the main finding is that the amplitude of performance drop decreases by the number of alternations. Another key finding is that even small changes in the new interface produced a significant performance drop for the entire previously learned interface (Chapter 7).

8.2 IMPLICATIONS

HCI researchers generally focus on skill acquisition, intramodal learning and transfer of learning. Now through describing retroactive transfer phenomena in this thesis, I aimed at encourage designers to pay more attention to the impact of introducing novel interfaces on previously learned skills because of the ubiquitous nature of interaction across applications. The interviews (Chapter 5) revealed that there are many situations in users' daily routine where they alternate between devices, interfaces, software, or operating systems for the same type of tasks (e.g., pointing, entering text, executing commands, etc.).

So designers and researchers should not assume that providing a new system, interface or device will replace the previous one, but it is likely to co-exist with the previous one. They should thus consider the transition from the previous to the new interface but also from the new interface to the previous one. Empirically evaluating retroactive transfer seems essential for ecologically valid investigation of interface design.

8.3 FUTURE WORK

8.3.1 *Investigating additional factors*

The experiment in this thesis, focused on similarity as it is a critical factor for interaction design (Bi et al., 2010). However, there were several factors I left aside that would require further investigation. For instance, manipulating the amount of practice and rest time might indicate whether expert users (i.e. skilled touch typists) would experience these phenomena to the same degree.

Also, one might investigate how the distribution of target frequency influences proactive and retroactive transfer. In the experimental design, I used a uniform distribution (i.e. each target had the same probably of appearing within a block). However, in real scenarios, the frequency of each character and bigrams depend on the language. According to results in sequential learning (Koedijker et al., 2010), the magnitude of the interference could be larger for frequent bigrams. In addition, one should investigate the impact of different modalities, e.g. gestures, on retroactive interference. Which modalities minimize retroactive interference? Finally, future research is necessary to generalize the results to real-world problems, e.g., real keyboard layouts.

8.3.2 *Modeling human performance when experiencing multiple alternations*

The first part of the thesis builds on *theoretical* findings from cognitive psychology to study retroactive transfer in HCI. The second part of the thesis relies on an *empirical* approach with both qualitative and quantitative experiments. As future work, we aim to investigate a *model-based* approach by elaborating computational models to predict human performance when alternating interfaces.

Computational models of human performance have several advantages. They can translate observations into an anticipation of future events and predict human behaviors. The outcome of the models are then used to understand, design, manage and predict the workings of complex systems and processes. Computational modeling can empower designers and researchers of HCI domain. Because the three elements of HCI (i.e., the human, the computer, and interaction) are extremely complex, models can help to explain such complexity (Oulasvirta, 2019). They can also help to design more efficient interactive systems without expensive empirical studies. Moreover, the powerful models can even be incorporated into interactive design tools (Bailly et al., 2014).

I plan to elaborate models of human performance at two levels of granularity:

- Behavioral models (short-term)
- Cognitive models (long-term)

Behavioral models are more understandable and easy to implement than cognitive models. In other hand, cognitive models are more flexible and can explain how the human behavior emerges from cognitive constraints.

8.3.2.1 *Behavioral model*

A promising approach to elaborate a predictive model of retroactive transfer is the model of Predictive Performance Equation (PPE), described in Chapter 3. PPE covers three phenomena: *learning* which is presented in the form of Power Law of Practice (PLP), *decay* that can appear in the form of an activation equation, and *distributed effect* which is equivalent to the rest time in retroactive transfer's experiment.

However, there are two potential challenges. The first one is to study how well this model can be extended to capture retroactive transfer phenomena and the effects of multiple alternations. It currently focuses on learning and skill acquisition. The second challenge is to integrate a mechanism to capture the effect of similarity on the three components of the model.

I have started to investigate how to introduce the effect of similarity on the PLP. As first step, I have modified the equation of PLP to integrate the amount of similarity, as well as the number of alternation. I tested this part of the model on the data of user experiment explained in the Chapter 6. The modified PLP have yielded progress in predicting retroactive transfer, but it still needs more work. Also, the type of targets which are static and dynamic need to take into consideration. The selection time for each condition predicted by the current model (up to now), is displayed in Figure 46. Implementing two other components are the future direction of this work.

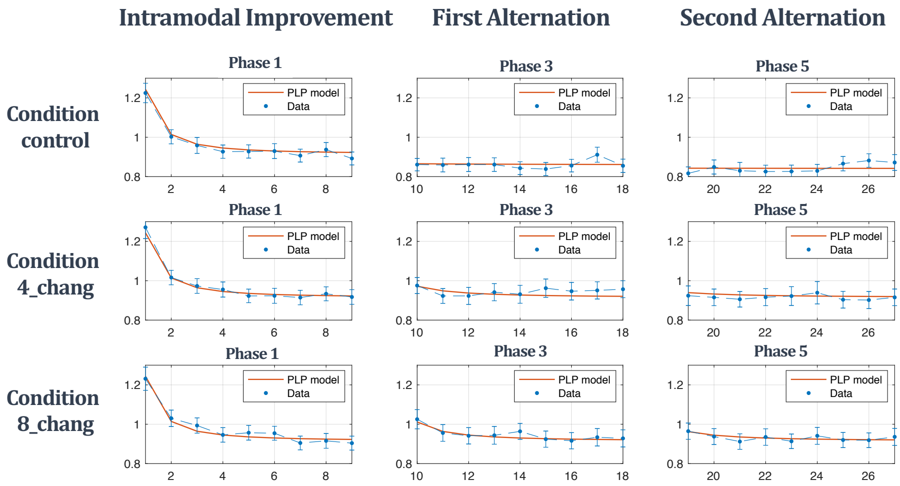

Figure 46: Model of retroactive transfer. The first row illustrates the learning curve while there are rest times in between. The two other rows illustrate the learning curve affected by retroactive interference by 2 different similar keyboard layouts.

8.3.2.2 *Cognitive model*

The long-term perspective is to elaborate cognitive models. One of the main advantage of cognitive models is their generalizability. The advantage of cognitive model over behavioural model is that the cognitive model can be used to derive new predictions for new relationships that go far beyond the original data (Busemeyer and Diederich, 2010).

Several approaches are possible to elaborate cognitive models. One approach consists of building models based on well established cognitive architecture such as ACT-R. This approach includes integrating many advanced cognitive components. ACT-R offers various interacting modules, mainly perceptual systems (e.g., vision module), motor systems (e.g., manual module), and memory coordinated through a production system.

A trend in HCI is to build simpler models using only a subset of relevant components of ACT-R, such as the proactive transfer model proposed by Jokinen et al. (Jokinen et al., 2017). Their model explains the negative impact of switching to a partially changed keyboard layout on typing performance. My work provides two main directions to extend this model. First, the results show that the dynamic targets influence performance time of other targets when switching to the new layout (proactive transfer). Such model should thus introduce mechanisms to explain how changed keys influence the performance of other keys. Second, the model could be extended to integrate phenomena related to retroactive transfer.

As described in Chapter 4, their model relies on some important components of the cognitive architecture of ACT-R (Anderson, 1982, 1983). I was expecting that the mechanisms like memory activation (Anderson et al., 1998) should explain the retroactive transfer. Since retroactive transfer is pretty much like the proactive transfer, but from new to old layout.

During this thesis, I started to investigate how to extend their model. However, I realized that the output generated by the simulation code (provided by J.Jokinen) does not capture retroactive interference phenomenon (see Figure 47). As it is shown the temporal performance drop (TPD) between Phase 1 and Phase 3 is not confirming an interference.

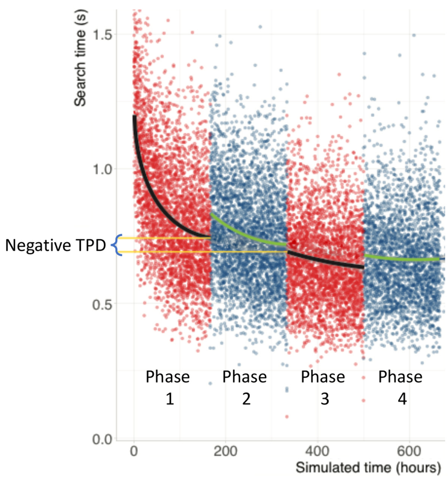

Figure 47: Retroactive transfer scenario, output of model developed in (Jokinen et al., 2017)

Therefore, to find the source of this problem, I've reimplemented the model. However, some theoretical flaws in their model have also been identified. As explained in Chapter 4, when there is a competition between two similar key's letters with different locations (i.e., between two chunks in declarative memory), the authors proposed to compare the utility values instead of activation values. Utility values are allocated to the production rules, and they can be compared when there are a conflict between similar production rules (in procedural memory). As future work, we thus aim to investigate how to exploit key components of ACT-R to elaborate a model capturing retroactive transfer phenomena while keeping simple enough to be easily integrated in design tools.

8.3.3 *Intelligent systems*

The ultimate goal is to integrate the above models in intelligent systems. Typically, intelligent systems with the capacity to capture alternations can avoid/reduce retroactive interference. For instance, they can provide some recommendations such as increasing rest time at a given alternation or increasing training to reduce the risk of interference. It can be a system that get different keyboard layout that is used in different devices as input (e.g., layouts in laptop, smartphone, etc.). When a new layout enters, the system recommends to use it, modify it (i.e., modify the key locations based on the previously learned keyboard layouts), gives the notification for finding the new key locations or gives the notification to prevent the possible errors.

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