COGNITIVE, PERCEPTUAL-MOTOR AND SOCIAL FACTORS IN TOOL MAKING IN CHILDREN

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

COGNITIVE, PERCEPTUAL-MOTOR AND SOCIAL FACTORS IN TOOL MAKING IN CHILDREN

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Children are proficient tool users; however, pre-school children are not proficient in every aspect of tool-related behaviors, in particular tool making. Considering the cognitive and social abilities of humans, this thesis ultimately aims to provide a new way of looking at human tool making. In addition, it is aimed to find facilitative factors in the process of tool making in children. Based on these motivations, five experiments were conducted using the 'hook task', in which children could make a hook shape with the given tools in order to pull a bucket out of a tall tube to reach a sticker. Result of the Experiment-1 showed that spontaneous tool innovation was very difficult for children. However, older children were better in tool making after observing modifications socially. On the other hand, tool making after social learning was predicted by inhibition capacities of executive functions and hierarchical representational abilities. In Experiment-2 and 3, we found that while adults based tool innovation and selection on the salience of the affordance of the tools, 5 and 6-year-old children were better in the process of tool making with familiar tool-task relation. We also showed the significant role of hierarchical representation and divergent thinking in the process of tool making. In Experiment-4, we found that 5 and 6-year-old children were better in the process of tool making in the dyadic condition compared to the individual condition. In Experiment-5, we demonstrated that there was no significant difference in the process of tool making between New Zealand and Turkish children in dyadic tool making.

Keywords: Tool making, tool innovation, ontogeny, hierarchical structuring, dyadic interaction.

ÖZ

ÇOCUKLARDA ALET YAPIMINDA BİLİŞSEL, ALGISAL-MOTOR VE SOSYAL FAKTÖRLER

Gönül, Gökhan
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Çocuklar alet kullanımında başarılı olsa da bütün alet-bağlantılı davranışlarda yetkin değillerdir, özellikle de alet yapımında. Bu tezin en nihai amacı bilişsel ve sosyal faktörleri de göz önünde bulundurarak insanların alet yapımı davranışına yeni bir bakış getirmektir. Bunun yanında bu tezde, çocukların alet yapımını kolaylaştırıcı etkenlerin bulunması amaçlanmıştır. Bu motivasyonlar doğrultusunda 'kanca testi' kullanılarak beş deney yürütülmüştür. Bu testte katılımcıların, uzun bir şişenin içinde bulunan küçük bir bakraçtaki çıkartmaya ulaşabilmek için onlara verilen materyali kanca şekline getirerek bakracı şişenin içinden çıkarmaları gerekmektedir. Deney 1'in sonuçları göstermiştir ki çocuklar spontane alet inovastonunda büyük zorluk çekmektedir. Fakat yaşça daha büyük olan çocuklar, alet üzerinde yapılan modifikasyonları sosyal olarak gördükten sonra alet yapımında daha başarılı olmuştur. Diğer yandan, çocukların yönetici işlevlerinin ketleme (inhibition) kapasitesi ve hiyerarşik zihinsel temsiller oluşturma yetisi, onların sosyal öğrenme sonrası alet yapımı sonuçlarının yordayıcıları olmuştur. Yetişkinlerin alet inovasyonu ve alet seçimi, aletlerin ne kadar göze-çarpan bir sağlarlığı (affordance) olduğuna dayanırken , 5 ve 6 yaşındaki çocuklar alet ile test arasında aşinalık olduğu durumda alet yapım sürecinde daha başarılı olmuşlardır (Deney 2 ve 3). Ayrıca bu deneyde, hiyerarşik temsiller oluşturma ve çeşitli-ıraksak düşünmenin (divergent thinking) alet yapım sürecindeki anlamlı rolü gösterilmiştir. Deney 4’te, 5 ve 6 yaş arası çocukların ikili iletişim halindeyken alet yapımında – tek başına yapmalarına göre– daha başarılı oldukları gösterilmiştir. Deney-5’te alet yapım sürecinde Yeni Zelanda’lı çocuklar ile Türkiyeli çocuklar arasında anlamlı bir fark olmadığını gösterilmiştir.

Anahtar Sözcükler: Alet yapımı, alet inovasyonu, ontogenez, hiyerarşik yapılandırma, ikili etkileşim.

To Jane Goodall

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In their contentious book, Lakoff and Johnson (2003) investigate and analyze the role of metaphors in our lives. One of the metaphors that they deeply study is the 'JOURNEY' metaphor: Life is a journey, love is a journey, etc. Using their JOURNEY' metaphor, I can say the following: PhD is a journey. In this amazing journey, I had the chance to work and interact with wonderful people, and this journey would be far harder without these people.

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CHAPTER 1

INTRODUCTION

At the beginning of the 20th century, Louis Leakey and numerous other researchers found many stone tools in Africa dating back to 1.8-2.6 million years ago. This was an amazing discovery but Leakey and his colleagues were not able to explain how genus *homo* came up with the idea of creating tools and how did they construct tools to solve problems. More precisely, how could genus *homo* have evolved higher level cognitive, social and motor abilities that are required for tool making?

For a long time, tool-related behaviors have been seen as a uniquely human ability, which distinguished the *homo* line from other species during evolution (Oakley, 1957). However, in the extant literature, it is acknowledged that other animals can use tools as well (Meulman, Seed & Mann, 2013). Especially chimpanzees and New Caledonian crows can go beyond using tools and make tools (Goodall, 1986; Weir & Kacelnik, 2002). Nevertheless, the number of innovations and propensity of tools make human tool culture incomparably complex in the animal kingdom (Mithen, 2003). What made us such flexible and creative tool makers and users? While the existing literature might provide some insight into understanding how our tool making capacity has evolved, the development (ontogeny) of this capacity is still not fully considered and understood well (Chappel et al., 2014). In other words, tool innovation and manufacture is the basis of human material culture; however, its ontogeny is hardly known. As Langer stated (1998, p.33), ‘‘cognition is a product of evolutionary and developmental processes’’, and we may not be able to understand one without the other. Whereas tools may fossilize or else prevail over geological time, cognitive and behavioral patterns do not. Therefore, developmental, evolutionary and comparative viewpoints are crucial in the investigation of tool making beyond the study of the artifacts as such. This means that only an evolutionary-developmental perspective within an interdisciplinary approach considering various factors (e.g. cognitive, social) may reveal our ability to make tools. However, the question arises as to how such an interdisciplinary approach can be devised and how we can determine which cognitive and social factors facilitate tool making.

The first step towards human tool-related behaviors is tool innovation or invention. During the last decade this exceptional human ability has attracted the attention of many researchers. Beyond understanding tool innovation phylogenetically, researchers in the last decade tried to understand it ontogenetically. In this thesis, we aim to reveal the perceptual-motor, cognitive and social bases of the development of tool innovation and other types of tool-related behaviors, e.g. tool manufacture.

1.1. Tool making in children

Tool making has two main steps: *tool innovation* and *tool manufacture*. *Tool innovation*, firstly, can be described as the novel use of a familiar object or novel method of construction of a tool to solve a problem (Nielsen et al., 2014). In other words, tool innovation means creating a novel tool spontaneously, that is to say in a non-social way (Carr, Kendal & Flynn, 2016). Whereas adults can readily innovate tools, children experience difficulty doing so. For instance, in a task in which children need to get a bucket out from a horizontal tube with the help of a pipe cleaner in order to reach a sticker, most preschool children cannot come up with the idea of creating a hook (bending the pipe cleaner) to solve the task spontaneously (Cutting et al., 2011). Studies have demonstrated that until the age of 7 or 8, children have great difficulty in solving tool innovation problems spontaneously, namely without any social help (Cutting et al., 2011; Beck et al., 2011). Although some previous studies attempt to explain why innovating a novel tool is so hard for preschool children, empirical results did not support these claims (see Beck et al., 2016). Therefore, the cognitive reason as to why preschool children have difficulty in innovating tools remain mostly unknown.

Tool manufacture, on the other side, means making tools after some social learning mechanisms. Although independent tool innovation is hard for preschoolers, children are better at making a tool after observing modifications made on the tool socially (Flynn & Whiten, 2010). Most of the 5-year-old and older children can solve the *hook task* if a ready-made tool or a tool making action is demonstrated by an adult (Chappell et al., 2013; Beck et al., 2011; Neldner, Mushin, & Nielsen, 2017). However, some 3 and 4 year old children still have problem in tool manufacturing (Cutting et al., 2011; Gönül, Takmaz, Hohenberger, & Corballis, 2018).

Children are not fully at a loss with innovating tools, though. They can select the functional tool if it is in the perceptual array (Beck et al., 2011) or in some cases they can say what kind of tool might be functional to solve tool innovation tasks even if they are not prompted to say so (see Chapter 3). These results might imply some imagination and simulation abilities. Children can imagine what kind of tool might be functional to solve a given tool innovation problem, but they may not be cognitively ready to implement their representation into actions, e.g. change the shape of a tool at hand (Gönül, Hohenberger, Takmaz, & Corballis 2018).

In the broader picture, these abilities are the basis of human material culture, and we believe that revealing the potential factors underlying these abilities might help to understand what made us different and distinguishes us in the animal kingdom. The cognitive bases of tool making have not been systematically investigated, developmentally. In order to fill this gap, the current thesis will initiate the systematic investigation of our tool making ability considering various factors. Besides, tool making studies are an inherently multidisciplinary research topic, as they are intensely investigated in comparative psychology, biology and cognitive sciences. Thus, this thesis might contribute to these interdisciplinary attempts from an ontogenetic viewpoint.

1.2. General aim and structure of the thesis

Although the literature and our studies shed some light on the factors underlying one type of making (tool making after observing modifications) there is still no systematic study showing as to why children are not ready to innovate tools independently why young children have difficulty in manufacturing tools. Some facilitating factors such as visibility of affordance are known. Nevertheless, these factors do not explain the reason why children are cognitively immature for making novel tools without help. Five-to-seven-year old children can solve quite complex problems (Klahr, & Robinson, 1981), and children can solve means-ends tool use problems via making causal relations between the tool and the target beginning from the second year of life (McCarty, Clifton, & Collard, 1999). Why can’t they create a novel tool in a task like the hook task? In this thesis we aim to unravel perceptual-motor, cognitive and social factors underlying tool making in 3-to-6-year-old children. Second aim is to provide inter-disciplinary perspective on the development of tool making. Lastly, this thesis also aim to provide a framework for the development of tool making, and explain why children have great difficulty in tool innovation particularly.

Chapter 2

This chapter is the scaffolding of the thesis. Children can use tools before they can make tools. There is a great developmental transition from object representation in the early months to tool innovation in the later years. Without understating what develops in the early ages, one might not understand the cognitive or social mechanism underlying tool making in later years. So that, in Chapter 2, first of all, the developmental literature is reviewed and discussed in a (mostly) impartial and objective way. Secondly, there is a great problem with definitions. So that, the definition(s) of the following concepts are provided in this chapter: object, tool, tool use, social learning mechanisms, innovation, tool making, and tool innovation. Third, there is a very popular trend –mostly in developmental psychology: ascribing to some higher cognitive mechanisms to infants in their early months. In this chapter, when actually infants can use tools, socially learn, and make tools will be discussed in the light of this critique. Lastly, this chapter is transdisciplinary. Since some terms used in this thesis originated from different disciplines, results from the relevant discipline are discussed.

Broadly speaking, there are three main views concerning the development of tool-related behaviors (mostly in tool –use literature): representational, perceptual-motor, and social-cultural views. While the *representational approach* puts emphasis on the symbolic thinking capacity of humans such as hierarchical representation (constructing hierarchical representations of sequential actions or constructing hierarchically structured shapes), creativity and divergent thinking, executive functions and inhibition, insightful problem solving and planning; the *perceptual-motor approach* highlights affordance relations, skill learning, and perceptual factors. Finally, the *social-cultural approach* emphasizes social cognition and cultural learning. As developmental, cognitive and social bases of tool making are in its infancy, we adopt and compare different theoretical approaches, and finally construct our own approach in the conclusion. Thus, the following three chapters are based on the results of experimental and explorative studies discussing different approaches.

Chapter 3

The ultimate aim of this chapter is to reveal the effect of two cognitive (or representational) mechanisms that have been hypothesized to underlie tool innovation and tool making, and to unravel the developmental change in years. Thus, in this chapter, we compared tool making capacities of 3 and 4-year-old and 5 and 6-year-old Turkish preschool children and underlying cognitive factors, namely hierarchical representation and inhibition.

Chapter 4

One sentence will appear in this thesis again and again: children have great difficulty in tool innovation. This difficulty may be related to the tool: pipe-cleaner, which is a very novel tool especially for Turkish children. Can children's tool making process be facilitated perceptual-motor factors? In this chapter, we mostly focused on the perceptual-motor factors, but we also aimed to generalize our findings related to hierarchical structuring with different tools and different age groups. We used three different tools in this study ranging from very familiar to novel.

Chapter 5

Cultural evolution of tools based on complex social interactions. Children not only learn from adults, but also from their peers. In this chapter, we focused on social (peer interaction) and cultural mechanisms.

Chapter 6

In this chapter, first of all, a general discussion of the empirical studies provided. Although our studies shed great light on the development of tool making, results of the studies could not be generalized into tool innovation. Tool innovation via changing the shape of a tool or constructing a novel tool is very rare in the animal kingdom, and human children adept to make novel tools after the age of 7 or 8. After a general discussion, in this chapter, first a working framework was offered for the tool innovation behavior in children. Secondly, a testable hypothesis was offered that would explain children's immaturity in tool innovation before the age of 7 or 8. Thus, in this chapter, it was argued that the 'idea of a functional tool' could precede tool making action, and children would simulate a functional tool but would not be able to construct the tool. The hypothesis was based on the simulation approaches and *ideo-motor approach*. In this chapter, studies for future research is also provided. Finally, we explain the theoretical gap between individual tool innovation and tool innovation during dyadic interaction.

CHAPTER 2

LITERATURE REVIEW AND THEORETICAL BACKGROUND

People use tools every day in different ways, such as using a computer word processor to record ideas, using a cup to drink coffee, stringing some beads, and a child using a toy rattle to play with another toy out of reach. Even these everyday examples show the indisputable complexity of human tool-related behaviors, the accumulated knowledge of human material culture, and flexible tool using ability of human compared to other animals. The huge role of tools and our spontaneous relation with tools in this complex human culture testify to the skill and/or ability of human being in using tools. This ability has been evaluated as a natural attainment of human cognition and complex social relations which have developed in the process of biological and social evolution (Ambrose, 2001). Although we can easily and readily use tools, making novel tools or using tools in a novel way (tool innovation) is an ability that develops later in a child's life (Beck et al., 2011). Tool manufacture, through changing the shape of a tool after social learning to solve a novel problem, is a challenging task until the end of the fourth year of childhood (Gönül, Takmaz, Hohenberger, & Corballis, 2018). Thus, the question arises as to why tool innovation and tool manufacture are abilities that develop later when compared to tool use. To respond to this question, this thesis has three aims. First, to review the perceptual-motor, cognitive-representational and social-cultural factors that are crucial for the fine-skilled tool-related behaviors capacity. Second, to explain the developmental transition from tool use to tool making. Third, to explain why tool making is difficult for young children and what is required for engaging in tool making from an evolutionary and developmental perspective. Achieving these aims will assist in finding an eloquent and persuasive explanation for the facilitative cognitive and/or interactive processes on tool making, which will reveal what distinguishes human tool making from another species.

2.1. Starting point: object representation and tool use

We are born into the world that is full of objects that we learn their means step by step, which is amazing; however, as Keen (2011) indicated developmental psychologists have not as yet investigated the issue of tool-related behaviors. Researchers concerned with early childhood development have not really examined how infants represent and use tools flexibly, make tools and solve problems with novel tools, and how the transition from tool use to tool making occurs. Although this thesis is not focused on the early days of infant development, it is noteworthy to explain the basic mechanisms of object and event perception that are assumed to be crucial for later tool use and tool making.

Tool making is a later developing ability. However, children pass through some developmental changes during this process. They perceive objects and event, represent them and act with objects. They might learn action possibilities with objects which would facilitate later tool making ability. Setting aside the nature-nurture distinction and nativist/empiricist debate, the developmental process from perceiving objects to tool use will be discussed in the following subsections.

2.1.1. From object perception to tool use

> *"The most advanced forms of human technology are rooted in our capacities to fashion the materials of our environment into tools and employ them adaptively in diverse contexts. Clearly, the hammer used by a toddler is far removed from the computer used by a scientist, but in the tool behaviors of young children, one may begin to see the first glimmer of our remarkable technological potential (Lockman, 2000; p. 137)."*

Human beings are somehow affected by our early exposure to objects and events, and this is still under investigation in that we might have some innate mechanisms to make the sense of these events and objects in the world (see Spelke, 1994). In the developmental and cognitive science literature, it is a moot point as to whether infants are equipped with some predispositions to make sense of the world (Keil, 2006). In particular, the nativist theorists have demonstrated in many studies that infants engage in certain kinds of information in their complex perceptual array more than other others both during pregnancy and at the very beginning of their lives (see Spelke & Kinzler, 2007; Simion, Regolin & Bulf, 2008; Spelke, 1994). According to these studies, infants may have some innately specified mechanisms that process some sort of visual data, such as face-like patterns or biological motion (for a review see Simion, Regolin & Bulf, 2008; Simion & Giorgio, 2015). Furthermore, infants may integrate cross-modal sensory information (Meltzoff & Borton, 1979), which may not be easy without innate tendencies. Spelke (1994) points out that even though some knowledge is innate, this domain-specific innate knowledge constrains infants' perception in the early months. Spelke (1998) also emphasizes that there are some innate guiding principles for infants to define and acquire the sense of the objects as a whole. However, how are objects represented as a whole when some part of the object is occluded? How does information related to objects enter the environment; in other words, how do objects become events in the environment? It is possible that these questions cannot be answered comprehensively without considering both the nativist and/or 'core knowledge' approaches described above, and the views that highlight the role of environment and perceptual-motor properties (Cohen & Cashon, 2006). Besides, there is also a third alternative in which children may learn the action possibilities of the objects and the environment (Allen & Bickhard, 2013).

Gibson (2015) and Gibson and Pick (2003) indicate that all animals are information collectors within their environment. In this ecological reality, physical objects and events are perceived with the help of motion, and this connection between objects, events, and motion has been shown in many studies. One pioneering study is Elisabeth Spelke's research with infants. Spelke (1990) emphasizes that the fourth month of a child's life is a critical time for the perception of object representation for occluded objects, but the crucial point is that the object should move. Making the object move facilitates infants' representation of objects. This issue may direct us to think about events as movements in the environment. However, although young infants are able to retain the representation of physical events for some time in their memory, it might be hard to state that their representations of events are in conscious control (Taylor, 2005), which will be discussed later. Taylor (2005) defines event perception as the capability of 'perceiving associations in the timeline', and Gibson (2015; p. 93) states that "the reality underlying the dimension of time is sequential order of events". What should be highlighted is that infants might be able to record events and objects implicitly which is related to priming and recognition, and their recognition of multilayered events is limited until they are eight-nine months old (Bauer, 2006).

While these studies seems very charming, there is a theoretical gap here: the very assumption that early appearing capacities share the same construct with later emerging abilities (see Kagan, 2008). Although we will give some examples about this conceptual gap in the later sections, here it is contented with emphasizing the difference between perception of objects in the early years and acting with tools in the later years. That is for sure that early exposure to objects facilitates tool use in the later years. However, the process may not need to go through perception to action, but entwined processes among perception, action and cognition.

The pertinent question is how early representations of objects and events are formed. The relevant literature has shown that even the capacity of a 14-month-old infant to store knowledge is limited without conceptual, spatial or linguistic facilitation (Feigenson & Halberda, 2008). A very young child's early representations might be mostly procedural requiring implicit memory (Bauer, 2006), and it can be claimed that their early representations are based on perceptual experience (for the critique of this point of view, see Brown, 1990). Taylor (2005) indicates that young infants can neither reach these implicit and perceptual experience-based representations consciously nor recall them at will. Thus, early representations might be perceptual rather than conceptual (Mandler, 2000). Conscious control of representations might require the developed ability to understand the meaning of an infant's experiences (Zelazo, 2004). In order to recall events at will, they need to have the ability to compare 'past' and 'new' experiences and find the similarities and differences between them (Taylor, 2005).

As stated previously, infants' representations are not fully under control of explicit awareness. Thus, they act on the objects if they see them; in other words, they can recognize objects, but they only make representations perceptually, not conceptually. Piaget (2003) explains this situation as the requirement for a representation to be symbolic in order to be a mental representation. Symbolic thought is the capacity to carry information in the mental even after some time of the perceptual event. According to Piaget (2003), competence for making representations 'mental' develops and becomes overt at around 18-24 months. However, recent studies indicate that symbolic though might develop as early as nine months (Bauer, 2006).

The issue of whether infants have long-term mental images or concepts about objects and events remains under debate (see Feigenson & Carey, 2003; 2005). Some researchers claim that infants in their early months have the ability to use their mental imagery for representations of locations and objects. In their inventively manipulated study, Clifton et al. (1991) show that in the dark, six-month-olds can adapt their reaching and grasping patterns according to the size of the object. According to these results, it can be asserted that infants can retain the representation of objects for some time as mental images. However, the critical question is how long the information is retained in the memory. In a study by Clifton et al. (1991), infants did not have to retain the perceptual unit for a long time. On the other hand, the *perception-action* cycle in Clifton et al.'s (1991) study might be more procedural.

In conclusion, young infants may have some innate principles for perception, and their mental representation might be perceptual at the beginning of their lives. In the process of the development of object representation, making an object move helps babies to construct the representation of the object as a whole. The connection between object perception, occlusion, and movements shows the close relation between representation of objects and representation of events. This is followed later by the infant developing object concepts which starts after the first nine months.

2.1.2. Perception, action and tools: How does an object turn into a tool?

This section shows how infants make a causal relationship between perceived objects and perceived events, and are not passive observers of the environment; rather, they act in the environment and with the objects. They go beyond the observation of events and start to produce events with the help of their various behavioral mechanisms which are crucial for later tool use. In this section, perception-action viewpoints on objects and tools will be highlighted concerning what the nature of a tool is.

Gibson's (2015) claim that all animals including humans are active information collectors in their environment is an ecological-realist view, which provides a connection between organism and environment. In the optical array of the environment, organisms as perceivers collect information. Gibson and Pick (2003) clarify the relation between organism and environment as being dynamic and reciprocal in which the animals adapt to and act inside the environment. Each animal has its own *niche* in the environment; in other words, it has history of adaptation there, and individual development and learning is located within its own niche.

Beyond being passive information collectors, animals are also motivated to explore the environment. With the help of *motivation*, infants *explore* objects (acting inside in their niche), they *learn* the environment and specialties of the objects, and the events in their environment. This *motivation for exploration* is mostly random in the first few months, and with perceptual development, it becomes an important source of *self-learning* (Gibson & Pick, 2003). Self-exploration and self-learning have a cascading effect on the later use of objects as tools. Keen (2011) comments that infants' impetus toward exploring objects and their early realization of finding the relations between objects and goals constitute their later *use of tools*.

Before explaining how objects become tools, it is necessary to clarify the distinction in the sense of what an object and a tool are. Gibson (2015; p. 34-36) describes an object that is concrete, has a definable surface, texture and layout, but tools are a special type of object that are "graspable, portable, manipulatable and usually rigid'', and they are "detached objects of a very special sort''. Connolly and Dalgleish (1989, p. 895) define tool as "a *device* for *working on* something." This raises the question of how an object becomes a *device* to act on or working on something.

Gibson (2015) emphasizes three different behavioral patterns for an object to be considered as a tool; the agent should use the tool for a *purpose*, it should be a *body extension*, and the agent should have the *capacity* to use an object as a tool. As noted previously, in the first months, the exploration of objects is random, as Gibson and Pick (2003) emphasized, and infants do not have conscious control of their behavior (Taylor, 2005). When a child sees a spoon after 11 months of age, she may easily adapt her grasping patterns according to the shape of the handle and the target. However, this ability can be based on a type of procedural learning working with perception. This reaching behavior with spoon could be evaluated as the beginning of simple problem solving and action planning abilities. However, it would be difficult to consider reaching behavior with tools as a complex action planning. Cox and Smitsman (2006) propose the term 'prospection' as the ability of action planning in early childhood. Based on these views, it can be claimed that object exploration and early *familiar* tool use (e.g., spoon) in the first year are preparatory behaviors for later purposeful tool use.

Beyond being purposive, objects are used as a *body extension*. Since the target for the object to be used (using it as missile, cracking a nut, eating something with a spoon) is in the environment, the organism needs to attain the target by using the facilitator factors of the object. If the nut has a strong cover, we need a strong object to crack it. We must use the selected object as a hand extension; thus, using the features of the tool in a way that goes beyond the capacity of the body the animal or person. There are also experimental evidence indicating that adults may perceive tools as the extension of their bodies (see Maravita & Iriki, 2004; Cardinali et al., 2009).

Gibson (2015, p. 35) implies that attaching an object to the body requires the "capacity to attach something to the body", but he does not explain this 'capacity'. Nevertheless, one of the most crucial parts of his point of view is that he describes the attachment of an object on hands as the synthesis of the organism and the environment, which erase the strict borders between the organism and environment.

Although these three criteria help us to understand the difference between an object and a tool, it does not explain the difference among the type of tools. Our capacity to define and object as a tool makes something a tool. However, tools may have fixed functions. For instance, a jar is a conventional tool and it has a canonical function. It is generally used to conserve foot or keep liquid inside. Thus, *artefacts* may be described as the tools that have canonical functions required to learn instrumental skills of the group. Legare and Nielsen (2015, p.689) define instrumental skills as "the technical toolkits of a cultural group." The function of an artefact might be understood individually or socially (Lyons et al., 2011). On the other side, an object (including artefacts) may inherently include an abstract new tool. For instance, a water bottle can be used as a missile if an aggressive animal approaches. A pipe cleaner can be bent to solve a problem and used as a hook, used to clean pipes (which is the main or universally defined function of it), used as a generic decoration independent of a particular function. The core element might be the competition among the inherent physical properties of the object for particular functions to be innovated, individual attempt to understand different use of the object, and the socially defined meaning of the object. The first two are the focus of this thesis.

2.1.2.1. Perceiving tools and acting with tools

How an object become a tool has been more or less clarified above, but there are still some gaps to be questioned: How do infants and children act on the target with an object in the events? What kind of capacity (cognitive and/or dexterity-skill) do the infants and children need to perceive an object as a tool? What environmental factors (contextual and perceptual) are required to make the connection between the target and the object? In response to these questions, there are three main connected mechanisms for making the relations between tools and events that initiate the tool use ability, which are self-learning and exploration, observational learning, and imitation. This section will focus on self-learning, and the importance of observational learning. The mechanism of imitation and other types of social learning mechanisms will be explained in section 2.2.3.

As stated above, events are perceived associations in the timeline and infants not only perceive events, but also act in the events (Gibson & Pick, 2003). Gibson and Pick (2003) claim that action and perceptual development have a reciprocal connection, namely perception guides action and action provides information for perception. This *perception-action cycle* explains the possible relations between objects (including tools) and events. They can follow the sequence of events and the role of objects in the events (Spelke, 1990). The relation between objects and events emerges early in the ontogeny and rapidly develops over the course of the first few years (Spelke, 1990). Infants and children have self-learning and exploration mechanisms to use objects in the events (Gibson & Pick, 2003), and they can have a procedural memory of objects with events (Taylor, 2005; Cohen & Cashon, 2006). Thus, using objects, exploring them with their hands and being in the events with the objects might facilitate their later tool use (Gibson, 2015; Gibson & Pick, 2003).

As Gibson and Pick (2003) point out, children are active explorers of their environment. In this active exploration, they learn the *affordance relations* of their environment including tools and acquire the meaning of the objects before perceptual properties, such as color and size. This process allows children to become skilled tool users with experience. What do children get with experience in sense of tool use? The next section discusses three critical issues: perceptual similarity, affordance, and skills found in the literature concerning tool use.

2.1.2.2. Tool use as affordance relations or tool use as a skill

Perceptual similarity and proximity concepts have been some of the issues emphasized by researchers who have investigated the perception-action aspects on tool use development. Considering these two factors, in their pioneering study, Bates, Carlson-Luden and Bretherton (1980) used six type of tools with different combinations of the same or different color and texture, and various spatial configurations between the tool and the target with 10-month-old infants (see Figure 1 Experiment 1). Their results reveal that when the tool and target have the same texture and color, it is harder for infants to solve the *means-end problems* compared to other conditions. They interpret their results as "at 10 months of age a child is more likely to solve tool-use problems" and "if he sees tool and goal as two objects, rather than as *one* continuous object with or without a visible spatial link (Bates, Carlson-Luden & Bretherton, 1980; p. 133)". However, they did not obtain clear results from their *spatial contact* manipulation. They conducted another experiment to observe the effect of spatial contact on means-end problems with the tools and targets that had different colors and textures. In the current study, the problems with the cloth and string were easier for the infants, and the most difficult were those with the stick and crook with no contact (see Figure 1, Experiment 2).

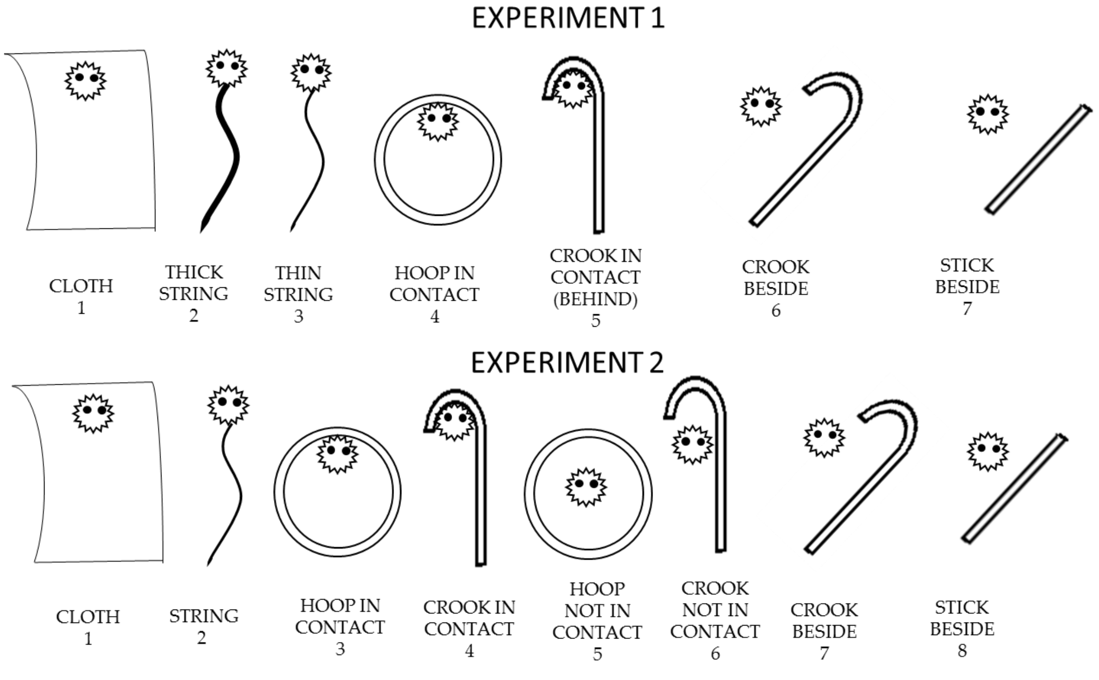


Figure 1: Means-end problems. Taken from "Perceptual aspects of tool use in infancy," by E. Bates, V. Carlson-Luden, I. Bretherton, 1980, Infant Behavior and Development, 3, p. 131. Copyright © 2018 Elsevier. Adapted with permission.

As it was emphasized in the section 2.1.1, children can retain limited information in the first year. Even if Bates et al. (1980) emphasize perceptual similarity for tool use, they relate tool use development to the symbol development. Based on their results, they assert that tool use requires having the knowledge of how to combine two different objects to solve the mean-ends problem. When the target and tool have the same texture and color, infants might not distinguish between two different objects, even in the conditions in which there is a spatial gap between the tool and the target. However, this begs the question what is perceived by infants first; the perceptual similarity between objects or the affordance of the objects?

Gibson (2015; p.94-126) describes affordance as the perception of the environment with ‘values’ and ‘means’. In this sense, events and objects in the nature “demand or invite appropriate behaviors”. The perceiver in the environment pay attention to the events and objects which afford something, and initially grasp the meaning objects before the surface properties, namely the perceptual similarities (such as color and form). Although Gibson (2015) clarifies the relation between tools and affordances, it was the study of Leeuwen, Smitsman and Leeuwen (1994) that went beyond explaining the basic affordance relations between actor, target, and tool, and advanced the idea of a higher order affordance structure.

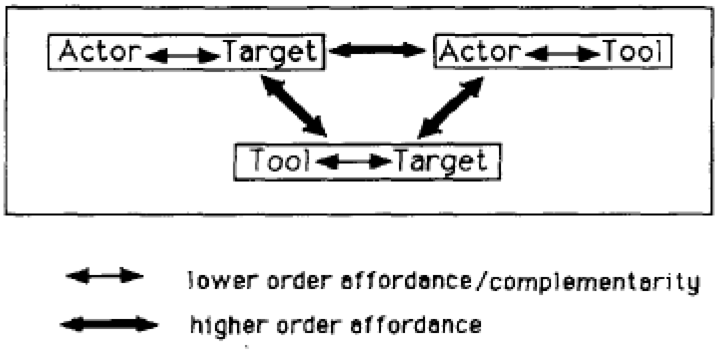


Figure 2: Higher order affordance structure. Taken from “Affordances, perceptual complexity, and the development of tool use,” by L. Von Leeuwen, A. Smitsman, & C. Von Leeuwen, 1994, Journal of Experimental Psychology: Human Perception and Performance, 20(1), p. 176. Copyright © 2018 American Psychological Association. Permission is not required for the reuse of this image.

The basic claim of Leeuwen et al. in this formulation (Figure 2) is that what affords is not only the tool, but also the target. Beyond it, the actors’ *goal* and *skill* and the physical constraints affect the higher order affordance relations. Perceiving the affordance structure (higher order affordance relations) means perceiving these *hierarchically structured events*. In the case of tool use, these hierarchically structured events are *embedded* relations; in other words, *actions that are directed* to the target embed actions directed to the tool. The actor is a part of these hierarchically embedded relations. For example, Figure 3 shows that the discontinuity between target and tool increases from left to right. This is because there are more subevents depending on the spatial configuration between the target and the tool for the actor to bring the target. In their study, Leeuwen et al. (1994) showed that increasing the complexity of affordance structure reduces younger (from eight to 22 months old) and older (from 23 months to 3.8 years old) children's success to approach or reach the target.

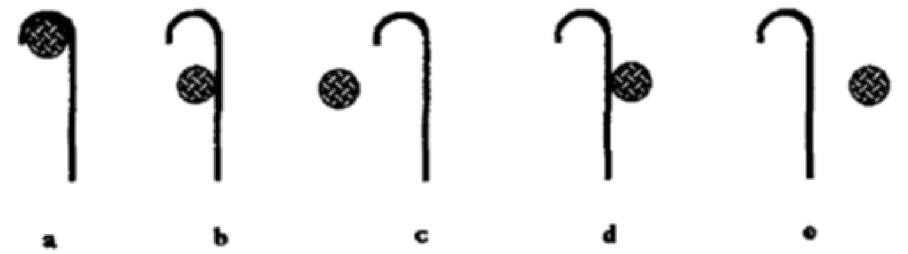


Figure 3: Different types of discontinuity between the target and the tool. Taken from "Affordances, perceptual complexity, and the development of tool use," by L. Von Leeuwen, A. Smitsman, & C. Von Leeuwen, 1994, Journal of Experimental Psychology: Human Perception and Performance, 20(1), p. 178. Copyright © 2018 Copyright American Psychological Association. Permission is not required to reprint this image.

The views on tool use emphasizing perceptual similarity (e.g. Bates et al., 1980) are not only criticized by the researchers that emphasize affordance relations, but also those, such as Brown (1990), who point to the role of casual reasoning. Brown does not disregard the role of perceptual similarity; however, she highlights that even young children can make causal relations between different physical realities and transfer their knowledge across problems. She asserts that perception-based-views on tool use originate from Thorndike's identical elements which are founded on the assumption that that two stimulus must have identical elements to transfer information from one to the other. However, the term 'identical elements' is a vague one, and an actor or perceiver in the environment may go beyond the surface relations (Brown, 1990). Thus, the crucial point may not be the properties of the input, but the organized behavior of the agent during tool use. Lashley (1951; p. 112-122) states that "the input is never into a quiescent or static system, but always into a system which is actively excited or organized" and "behavior is the result of interaction of this background of excitation with the input from any designated stimulus''. This is why, according to Carl Lashley (1951), we need to understand the serial order of actions or the syntax of movements in skilled actions.

Lashley (1951; p. 122) gives two examples of skilled actions which require the temporal coordination of muscles: reaching and grasping. These two basic behavioral patterns have been investigated in depth, especially by researchers seeing tool use as a skilled action. The syntax of movements in skilled actions can be understood through these three sets of events: (1) 'individual adaptive acts', (2) 'determining tendency', and (3) the 'syntax of the act' ('a generalized pattern or schema of integration'). Even if different researchers use different terms for these three set of events in tool use, it can be seen that they mean similar things.

Bruner (1973) states that skills have three main parts; basic intention to trigger action, feedback, and action patterns in between them. This classification is very similar to that of Karl Lashley pertaining to skilled acts. To explain this triple formulation in tool use, spoon use is a good example. The spoon is one of the first tools that children encounter in their first year of life in Western cultures; thus, it has been commonly used in the first research into tool use (see Gesell &Ilg, 1937; in Connoly & Dalgeish, 1989). The study of Connoly and Dalgleish (1989) is one of the most comprehensive and detailed works on how infants acquire the skill of using a spoon. In their research, they recorded the spoon use of a group of infants every month starting from 11 until 17 months. They found that more adult-like grasping patterns (e.g., radial grip), faster attempts to eat food with the spoon, using preferred hand for the spoon use, and adapting their hand grips according to the different conditions largely depended on the age of the infant. The role of maturation on spoon use and the spurt of tool skill between from 11 to 17 months were described in great detail in their study. Thus, this study reveals that the syntax of movements or action patterns improves in tool use with maturation and experience.

Lockman (2000) emphasize both skill development and affordance relations in order to explain the gradual development of tool use ability. In this framework, the capacity to use tools develops through detecting and relating affordances with *self-exploration* and *trial-error* learning. Beginning from the very early months infants create the relations between tool-to-surface and tool-to-object, and make the localization of objects in their environment in these combinations. They not only detect/relate affordances and localize them in the environment, but also act on them in the environment with their action capacity base on both their evolved hand-body shape and actions that they undertake in other contexts. Thus, infants' trial-error behaviors, self-exploration of the objects, and their capacity for action and learning how to act on the environment shape their later tool use.

In this section, theories supporting the ideas of perception-action are presented and compared. The general tendency in these views is to see tool-use as perceived learning process. Most of these views criticize the perspectives addressing tool-use as representational/conceptual mechanism, namely relational/causal learning and/or insightful problem solving. The next two sections introduce the views that tend to see tool use as a conceptual capacity and problem solving ability. However, before moving on, it may be crucial to address perception-action identification (or considering perception of objects and manipulating or acting on objects equally the same thing) problem before introducing cognitive perspectives on tool use development. As Langer (1998) states, even if perception is a very big font of information, there is not enough research to claim whether they are parallel or cascade processes. The first problem is that while the manipulation of an object is a constructive activity, perception of objects is a receptive process (Cohen & Cashon, 2006). For example, studies show that infants categorize objects according to certain perceptual patterns much earlier than manually composing objects in different categories. More to the point is that these two processes of perceptual categorizing do not seem to affect the subsequent manual composing of children (see Langer, 1998, p. 43-46 for a review of these studies). Based on these studies, it may be forehandedly affirmed that what is overlooked (by perception-action viewpoint) is the role of cognition, and the onset-offset time difference between the biological development of perceptual capabilities and motor behaviors. Thus, it can be said that some abilities may be more stage dependent than the gradual increase with exposure to input and learning.

2.2. Beyond perception, affordance and skill: Representations for tool use, and tool use as problem solving

As the behavioral tradition waned, cognitive tradition gained a great deal of leverage in explaining tool-related behaviors against the theories underscoring perception-action, skill development, or affordances. This change produced many intact questions, such as "Do infants make causal relations while using tools?" and "Do they go beyond perceptive or affordance relations in tool-related behaviors?"

Studies show that even 27-week-old infants might perceive causality, and parse subcomponents of the simple physical events and construct cause-effect relations (Leslie & Keeble, 1987). Based on these results, it can be inferred that children start to make causal relations beginning form early months; however, it is after their 14-18 months of age that they reach the capacity to make mental images and go beyond the procedural perception-action relations (Bauer, 2006; Mandler, 2000; Taylor, 2005; Piaget, 1954, 1970). Langer (1998) indicates that at six months, infants have the capability to make serial object manipulations 'one-at-a-time', but it is after 12 months that they reach the capacity to make manipulations of 'two-at-a-time', which is a developmental transition from serial to parallel manipulations (e.g., from shaking one toy serially to handling two toys with different hands at the same time). Parallel manipulation of two objects requires the splitting of the child's attention. It is by the age of 18 months that children start to make both complementary classes (classifying objects according to their perceptual similarities) and functional equivalence (for example, they can both use a toy or a stick to reach a target) of objects. Thus, the question of how this transition from making simple causal relations beginning from six months of age to making higher order classification and functional understanding of objects by 18 months of age is posed.

2.2.1. Tool use as insightful problem solving and action planning

Cognitive views on tool use originate from Köhler's (1957) investigations into *insightful problem solving* of apes and Piaget's (2003) views on the development of intelligence in children. In this section, first Kohler's (1957) and Piaget's (2003) views regarding tool use are presented. Then, other views based on cognitive perspective will be explained and compared.

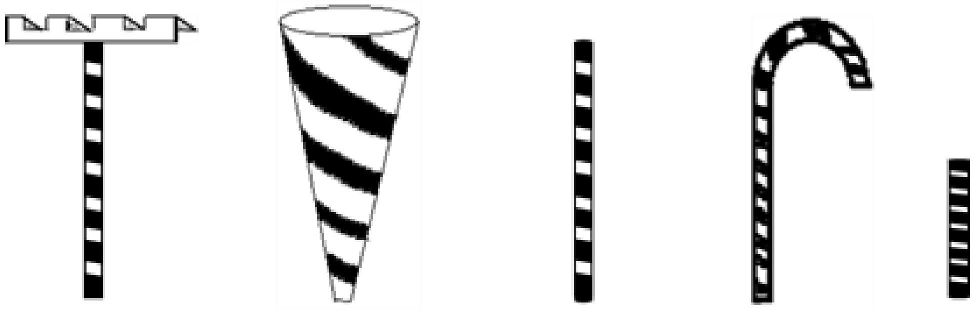
First, it is crucial to emphasize that the cognitive aspects of tool use development addresses the tool related behaviors of animals as a hallmark of intelligent behavior. Based on the results of his experiment with chimpanzees, Köhler (1957) presents tool-related behaviors as insightful problem solving in which the animal needs to combine information between the tool(s) and the target in its surrounding by insight, although the insight can be facilitated by perceptual (e.g., proximity between the tool and the target, whether the tools are with the animals' sphere of attention) and motivational factors (e.g., hunger; if the target is food, such as a banana which was used as the target in some of Köhler's experiments). Piaget (2003) claimed that insights for tool related behaviors as investigated by Köhler (1957) starts to develop in stage V between 10-18 months. However, the sequential manipulation of objects starts at stage IV, the time that infants start to manipulate more than one object. Through stages V and VI, infants start to use objects with purpose and undertake generalizations from their trial-error behaviors. During stage VI (after 18-24 months), the infant can perceive the relations among objects and targets mentally, namely by their capacity to make mental representations (Piaget, 2003). These transitions between stages may also explain why children in their first year cannot solve means-end problems without perceptually facilitating the target and the tool and the proximity between them. In related vein, Keen (2011) points out that well-structured sequential actions that are constructed on previous actions and complex planning for movements start to be seen, especially in the second year of life. McCarty, Clifton and Collard (1999) show how infants and young children can build up tool use problems piecemeal with increasing age. The authors investigated a group of children using a spoon with a differently oriented handle. As children have a tendency for handedness after seven months of age (see Connoly & Dalgeish, 1989), changing the position of the handle of a spoon creates a problem to be solved. While 19-month-old infants can change hands for the target action (eating), younger infants (nine and 14 months) are not able to do this. Their results show the role of age on selecting the appropriate action in the process of sequential action in order to solve the problems while inhibiting handedness. Other studies also show that planning abilities with a spoon or other tools improved from nine months to 2.5 years of age (McCarty, Clifton, & Collard, 1999; McCarty, Clifton & Collard, 2001; Cox & Smitsman, 2006).

Brown (1990) criticized perception-action views, and drew attention to deep structural principles that provide to make causal relations in different tool use problems. Even if the perceptual features and context are different, young children can infer the causal mechanism behind the problem and transfer it to the other problem. Furthermore, making causal relations and transferring them to the other problems starts at an early age and does not strictly change with age. Although physical similarity is important, it is not the fundamental principle of transfer. The reason why making causal relations is essential is that "a search for causal explanations is the basis of broad understanding, of wide patterns of generalization, and of flexible transfer and creative inferential projection -in sum, the essential elements of meaningful learning (Brown, 1990; p. 107)".

Brown (1990) criticizes early studies for not manipulating tool use experiments in an appropriate way and not including another attributes of tools, (such as length, rigidity, and whether the tool affords pulling and pushing) except for perceptual similarities. She conducted two experiments and used a set of tools fetching an interesting target. In the learning phase of the first experiment, two feasible tools for pulling, a long rake and a long hook, were given to three groups of children (17-24, 25-30, 31-36 months). They needed to use the tool as 'means for fetching' the target. If they did not engage in the action, the pull action was demonstrated by the mothers and the researchers waited until the children repeated the action three times. In the transfer phase of the first study, a set of one feasible tool (appropriate for fetching the target) and some unfeasible tools were given to the children (Figure 4). The results of the first study showed that younger children needed more help from their mothers' help than the older ones; however, in the transfer trials, there was no significant age difference. In the transfer phase, the children can easily select the appropriate tool for fetching the target, and they do not have the tendency to select the perceptually similar tools. Furthermore, the children prefer rigid tools, even if some of the non-rigid tools are perceptually similar to the ones that they used in learning phase.

In the second study, the tool preference of children from 24 to 42 months was identified in the learning phase with six set of tools (4 tools in each sets: a hook, a rake, a stick, and a stick with a trimming) with the same basic design as in the first study. The color, rigidity and size of the tools were manipulated. In the transfer phase, three tools (one preferred tool, one manipulated version of the preferred tool, and another functional tool) were presented in each of the six sets, according to the preference of children in the learning phase. Various factors were manipulated in each set, and the results showed that children select functional tools (rigid ones or those long enough to bring the target towards them) in transfer phase independent from their tool preference in the learning phase. For example, if there was one same-colored and different colored rake (between the learning and transfer phases) in the transfer phase, their preference appeared to be random (52% preferred the same-colored tool, 46% preferred different-colored rake). On the other hand, the children selected the most functional tool if there were two or more functional ones but would show distress if there were no functional tool.

Study 1
Learning Trial



Example of Transfer Trial

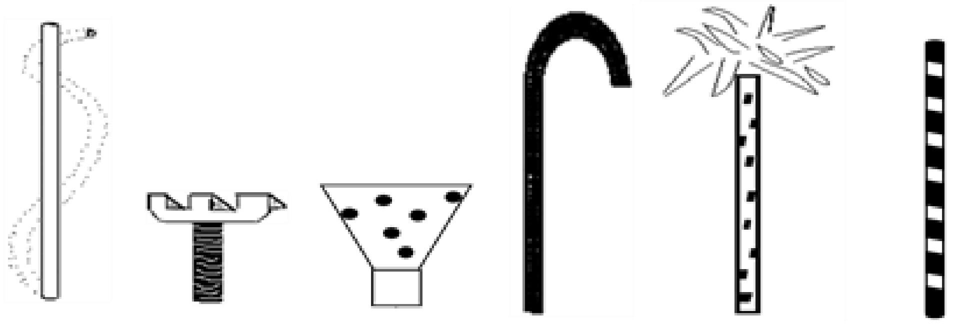


Figure 4: Tools used for means-end problems. From "Domain-specific principles affect learning and transfer in children," by A. L. Brown, 1990, Cognitive Science, 14(1), p. 116. Copyright © 2018 John Wiley and Sons. Adapted with permission.

Brown (1990) claims that transfer in learning for fetching the target is not strictly age-dependent. As pointed out by Rat-Fischer et al. (2012), children can understand the task requirements to reach the target after 18 months. Their results showed that older children (18-20-22 months) can reach the target with a rake overcoming the spatial gap between the tool and the target. For the tool use tasks (at least for the tasks require to pull or push the tool to reach the target) maturation might be a crucial factor. On the other hand, the role of experience and perceptual similarity should not be disregarded. Based on the Thorndike's

(1898) ‘law of effect’ and Gibson and Gibson’s (1955) theory of perceptual learning, McCarty and Keen (2005) showed that using spoon with radial grip in infants of age 12 months can be facilitated by perceptual exposure to the spoon in the same orientation for a block of trials. However, results from the spoon use might be hard to generalize to other types of tools since spoon use requires self-directed action (see Keen, 2011).

Based on the literature addressed so far, the broad picture and present situation on the development of tool use can be described as ‘’Perception, cognition, and motor development are so intertwined and related that it is usually unwise to study a single process in isolation’’ (Keen, 2011; p. 3). However, a unified perspective on cognitive development including perception, cognition and motor development, and considering dynamicity of behavior, and dexterity of the child may be too ambitious an attempt (Taylor, 2005). Instead, researchers, especially in the cognitive camp, investigate the main mechanism of tool related behaviors. One of the cornerstone attempts in this sense was the work of Ann Brown which originated from the cognitive tradition (Köhler’s and Piaget’s studies) as mentioned above. The two other main attempts in cognitive tradition are (1) those emphasizing to make symbolic representation and to construct anticipatory imagery (Bates et al., 1979), and (2) those making hierarchical representations (Greenfield, 1991), which will be mentioned in the following subsections.

2.2.2. Mental imagery and symbolic development

Although the debates on the structure, and even the existence, of mental representations have their merits derived from discussions in philosophy (for a brief review see Pitt, 2017), mental representations also came into prominence in cognitive science beginning from its early times adopting two distinct approaches. One camp tended to see the structure of mental representations as logical or propositional as support by Pylyshyn (1973) and the other camp proposed the analogical or image-like (pictorial) side of mental representations without disregarding the existence of propositional side of thought (Shepard, 1978). Pylyshyn (1973; p. 1-4) does not reject the existence of mental images either; he just differentiates between ‘what is stored?’ and ‘how we acquire and use this knowledge’, as many cognitive scientists do. He asserts that we do not have conscious access to the propositional mental concepts, unlike the pictorial type of mental images that are consciously controlled. This differentiation has always been made in psychology and cognitive science with different words, such as how or what knowledge, procedural or declarative memory, implicit or explicit coding, conscious or unconscious control, perceptual-motor or conceptual/representational system. However, it was Piaget's (1951; 1954; 1964; 1970) works that first conceptualized and unraveled the structure and development of mental representations in children. He underscores that symbolic thought provides for the construction of mental images beginning after the age of nine months, and then emerges especially after 15-18 months. However, spontaneous conscious control over symbolic thought arrives even later, by the age of three to four (Zelazo, 2004).

A symbol is a means of referent for referrer(s). In other words, symbols are the representations of some units or domains in the world. Symbols may have shared meaning systems, such as language, or the term symbol may also refer to the mental representation of perceptual units. Due to the developed capacity for symbolic thought, we are able to represent the world symbolically and consciously have control over these symbols even without the existence of the perceptual units, which is called psychological distancing (Callagan, 2013; Liberman & Trope, 2014) or internalization (Piaget, 1964). As Callagan (2013, p. 975) states, "symbols and symbolic thought enable us to distance ourselves from the present and entertain the past, the future and imagined".

Bates et al. (1980) assert that there is a strong positive correlation between tool use, and social and *symbolic* development. They point to this possible connection with examples from some studies showing that children with difficulties in language development also have problems in non-verbal tasks which requires *anticipatory imagery.* While explaining the link between symbol development, tool-use and anticipatory imagery, Bates et al. (1979) refer to the children's ability in completing perceptual distance between tool and the target, which requires transformation of mental units. For instance, when there was no contact between the tool and the target, the accomplishment of the task requires participant to *anticipate* or *foresee* target-tool link (Bates et al., 1980). Although Bates et al. (1980) claim that there is a type of correlation between symbolic development including *language* and *tool-use* via symbolic thinking, it is not easy to claim that the possible correlation was clearly explained in their paper except for emphasizing anticipatory imagery.

At this point, emphasis should be placed on the difference between language understanding, and intentional control of language use and language production during development, as Callaghan (2013, p. 974) states, "for all symbolic domains, the contrast between use and understanding must be considered in conceptualizations of the onset of symbolic functioning". By the same token, young children may have a precocious capacity to use symbolic artefacts, although it may not prove that they have consciously verbalize them nor that they have a reflective awareness of the relation between the referent and the symbol while representing symbolic artifacts (Callaghan, 2013). It is only by the age of three that children begin to create imaginative actions around artefacts even if the materials are not in the perceptual array (Lillard, 2002); however, the comprehension of gesture-symbol (before two years) relation precedes artefact-symbol relation (after two years), which shows that the conscious production of symbolic relations comes later than comprehension of symbolic relations (Tomasello, Striano & Rochat, 1999; Dick, Overton & Kovacs, 2005). Therefore, this begs the question of what the general picture is, and furthermore how language, tool-use and symbolic thought might be related.

From one perspective, language can be seen as an *internal syntax* and while motor control of hands might be considered as an *external syntax* (Stout & Chaminade, 2012). The grammar of action and grammar of language might share a main evolved system (Moore, 2010), which may be our symbol making ability (Deacon, 1997; Bates et al., 1979).

Infants begin to make referent-word connections beginning from six months and start to parse words soon afterwards, parsing words might parallel action parsing in tool-use, and this parallel processes might be based in similar brain parts (Broca's area) and representational processes (hierarchical structuring). However, language and tool-use development becomes autonomous after the age of two, and there is an increasing complexity in generating hierarchical representations from three years onwards (Greenfield, 1991). These theoretical assumptions and results of studies lead to the next section.

2.2.3. Hierarchical representation/structuring, cognition and tools

> *"The use of tools lends itself well to the study of problem solving because children must engage in planning that reveals hierarchical organization in their mind" (Keen, 2011; p. 7).*

> *"Complex motor planning (e.g. for sophisticated tool making), language and music all involve tree representations, because they all rely on hidden but important intermediate-level organization that*

> *must be inferred if the visible sequential surface (the terminal 'leaves' of the tree) is to be correctly parsed or executed." (Fitch, 2014; p. 353-354)*

Hierarchical structuring and/or organization is one of the most highlighted terms in the short history of cognitive sciences, beginning from Carl Lashley (1951) followed by Noam Chomsky (1957) and other scholars. Even the researchers emphasizing perceptual aspects; e.g., Leeuwen, Smitsman, & Leeuwen, (1994), point to the hierarchical complementary relations between tool and target that are to be perceived by the actor. However, their formulation on higher order affordance relations between tool, target, and actor do not explain how these hierarchically embedded relations are constructed by the actor. Langer (1998) claims that young children's ability in making three level classifications (for example, separating three types of colored cups into three classes according to their colors) shows their ability to make a "hierarchization of nested classes forming a genealogical tree structure" (Langer, 1998, p.40). Greenfield (1991) calls this ability to parse sequential actions '*hierarchically organized sequential behavior*'.

In its very basic sense, hierarchical organization means connecting subordinate elements on superordinate ones. This core ability has been seen as a unique capacity of human language (see Fitch & Hauser, 2004; Senghas, Kita & Özyürek, 2004). On the other hand, it is claimed that the hierarchical organization of both object/tool use (or manipulation/construction) and language not only share similar brain pathways especially before the age of two, but they also have identifiable representational similarities (Greenfield, 1991).

There might be two types of focus in the sense of 'hierarchy' in the tool-related-behavior literature: first is the *outside hierarchy* and second is *inside hierarchy.* While *outside hierarchy* (see Figure 5) can be the hierarchical presentation of actions (see Whiten et al., 2006; Flynn and Whiten, 2008a) or the total number of hierarchically embedded parts of an end-state tool for the target task (see Cutting, 2013), the cognitive capacity to represent of hierarchically embedded units or classifying sequential actions hierarchically might be called *inside hierarchy*, as can be seen in language and object combination (Greenfield, 1991), imitation (Byrne & Russon, 1998), or categorization (Langer, 1998). The latter is the representational capacity to execute and process *hierarchically embedded structures or actions* (Figure 5), which is the focus in this thesis. As the term 'hierarchical organization' is intertwined within the vast literature and varied views, only the literature related to tool and object manipulation in terms of hierarchical organization will be considered and discussed in this section. First, the studies of Patricia M. Greenfield and her colleagues, using similar tasks will be introduced, since their terms and formalizations are used extensively in the literature. Then, in the light of the studies, it will be discussed whether there is a domain general mechanism to process sequential information to engage in hierarchical organization.

During the manual combination of objects in a ‘construction activity’ or ‘tool use’, the actor uses their hands to combine parts in order to accomplish the end-state structure. This end-state structure may require not only combining objects sequentially, but also organizing them hierarchically. In the ‘manipulating serial cups’ study, Greenfield, Nelson and Saltzman (1972) found that the strategy employed to nest cups of varied sizes changes from children aged one to three years. While 11-to-16-month infants use the simplest strategy in which the cups are nested linearly, namely the *pairing method*, in a further strategy often utilized from 16 to 32 months, the other cups are placed into one stationary cup (*pot strategy*). The method which requires a hierarchical organization is the *subassembly method*, which is distinguished by the strategy of pairing two cups and putting the already-paired two cups together into a third cup. The latter strategy is the most often used at the age of three.

When children reach the third year of their life, combining actions hierarchically with the serial cups is very easy. In the later years, they can go beyond combining hierarchical actions (Greenfield, Nelson a& Saltzman, 1972; Greenfield, 1991), and start to construct familiar hierarchical shapes such as houses with parts. Reifel and Greenfield (1983) demonstrated that seven-year-old children put more *parts* (e.g., doors, windows, roof etc.) in the process of construction of a house (*whole*) with blocks than four-year-old children.

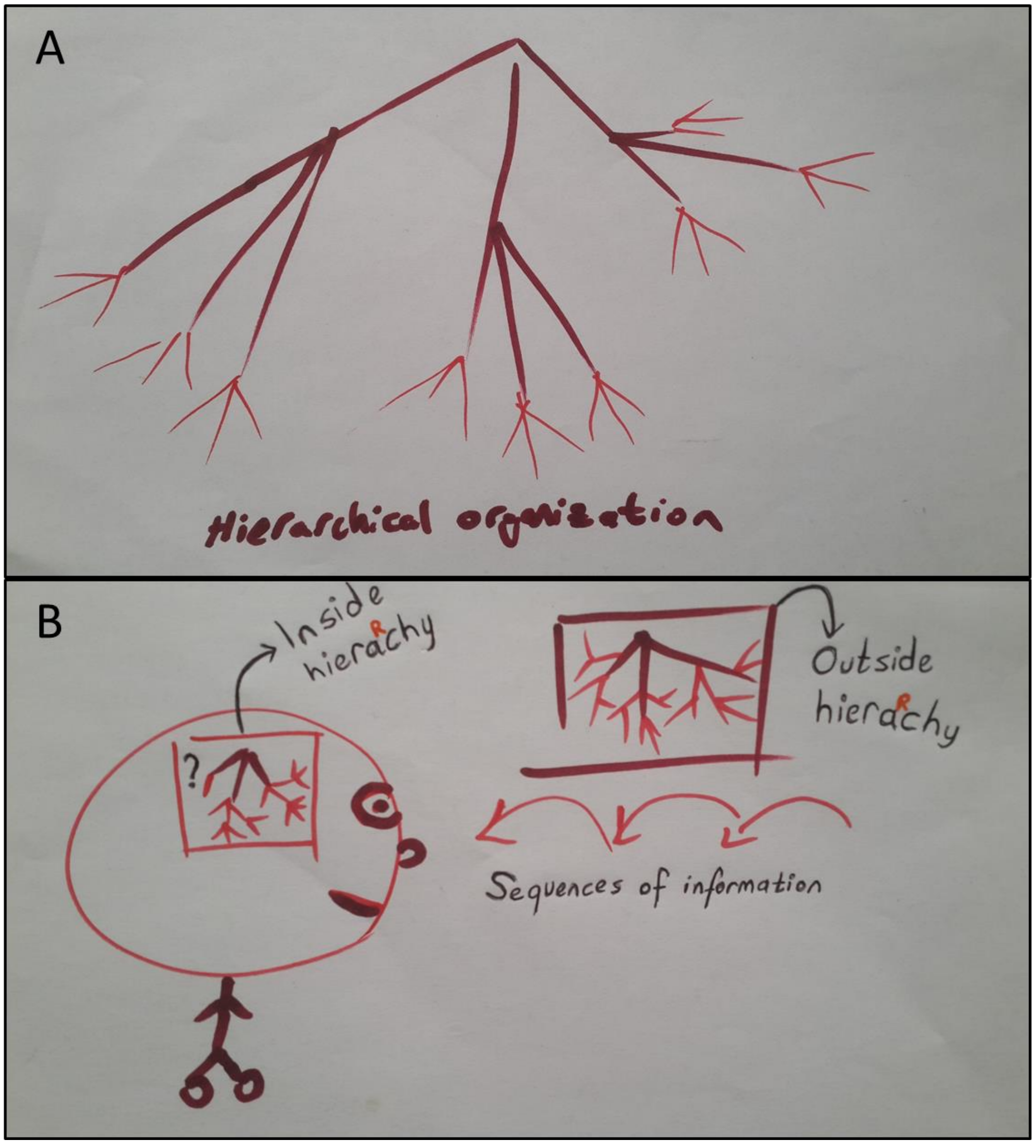


Figure 5: Hierarchical organization (A), and inside and outside hierarchy (B).

Beagles-Roos and Greenfield (1979) show that preschool children are not only capable of constructing hierarchical three-dimensional familiar shapes spontaneously, but can also construct three-dimensional familiar shapes (e.g., hierarchically structured flower shapes) presented in two dimension (as a picture). Their results also indicate that there might be a developmental transition in the fifth year of life in sense of constructing hierarchically complex shapes. However, in these studies children were required to constructed shapes with which they were familiar, and this leads to the question of whether children can construct hierarchically embedded novel shapes. A study by Goodson and Greenfield (1975) showed that especially after five years of age, children can parse their actions hierarchically and use different parts for different roles during the construction process of novel shapes. A similar pattern of results were shown in a study by Greenfield and Schneider (1977), in which children were asked to copy a novel hierarchical tree shape with straw (Figure 6). The complexity of the shapes gradually increased from three-year-olds to those aged five, and children become competent in constructing hierarchical tree structures after the age of five.

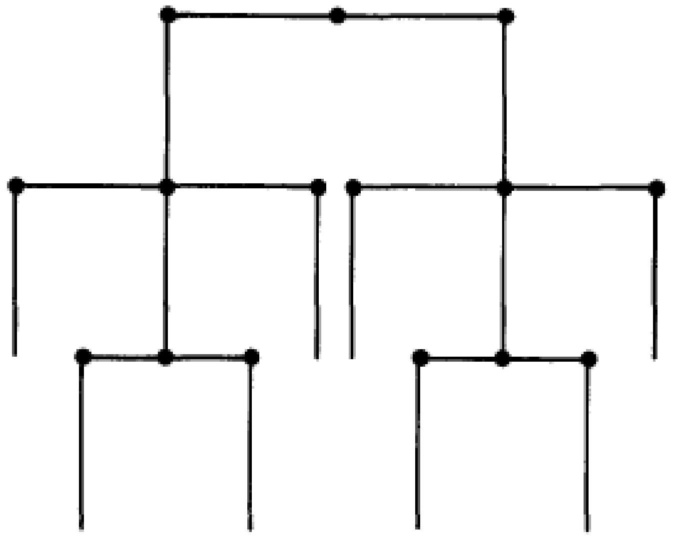


Figure 6: Hierarchical tree structure used by Greenfield and Schneider (1977). Taken from "Building a tree structure: The development of hierarchical complexity and interrupted strategies in children's construction activity," by P. M. Greenfield, & L. Schneider, 1977, Developmental Psychology, 13(4), p. 302. Copyright © 2018 Psychological Association. Permission is not required for the reuse of this image.

The next discussion point is whether hierarchical organization is a domain-specific or a domain-general capacity. Greenfield (1991) indicates that language, and tool-related behaviors including object construction require the hierarchical structuring of representations. She argues that tree structures in grammar are more than conceptual tools; that is, the infant's ability to structure sequential stimuli might be observed in their merging of action and also construction behavior. She claims that there are parallels between language development, and action merging in tool use, and that tree structuring of sequential actions and stimuli are processed in Broca's area. Although her argument received some harsh criticism (see Open Peer Commentary of the target paper, Greenfield, 1991), she refers to research that supported her claims, and other studies later reconsidered her opinions. In order to test the very idea that hierarchical representation of sequential stimuli is a psychological and neurological construct, and hierarchical construction and language are processed in similar brain areas, Grossman (1980) collected data from patients suffering from neurological loss, from which it was clearly shown that Broca's aphasics could not represent and construct hierarchical tree structures. Similar results were shown by other researchers. Cromer (1983) found that school children who had a severe type of Aphasia (receptive aphasia) also had a problem with hierarchical structuring and drawing hierarchical shapes. However, Kamhi, Ward and Mills (1995) claimed that they were not able to generalize these results with five-to-seven-year-old children who had specific language impairment. Although Kamhi, Ward and Mills (1995) attempted to test the viewpoint with other tasks and measures, unfortunately their study included too many measures and too many tasks with relatively small sample size. Therefore, considering their participants had mild language disorder, their results should be read with caution.

Grossman (1980) and Cromer (1983) go beyond language and object construction arguing that there might be a central processor or central planning ability that helps to structure behavior hierarchically. Cromer (1983, p. 144-145) states that "thoughts and intentions are not themselves temporally ordered and that to produce behavior a central planning mechanism is necessary in order to convert them into events that occur in real time". A similar claim was recently presented by Fitch (2014) as the Dendrophilia Hypothesis, in which he argues that "humans have a multi-domain capacity and proclivity to infer tree structures from strings, to a degree that is difficult or impossible for most non-human animal species" (p. 352).

Byrne and Russon (1998) place special emphasis on a central processor for imitative learning, rather than defining imitation as a domain specific process, indicating that socially learned behavior is hierarchically organized. They claim that imitation consists of two levels: action and program level. While the action level is based on sensory-motor copying of linear sequences of movements, the program level is the true imitation that based on hierarchical structuring of elements. They define program level imitation "as copying the structural organisation of a complex process (including the sequence of stages, subroutine structure, and bimanual coordination), by observation of the behaviour of another individual, while furnishing the exact details of actions by individual learning" (p. 676). However, this leads to the question of how social cognition in general contribute to tool-related behaviors, which will be discussed in the next section.

2.3. Social aspects of tool-use behavior

Until now, mostly individual learning mechanisms and environmental factors on tool-related behaviors has been emphasized. It has been highlighted that although children have the motivation to explore their environment in the early months and solve simple means-end problems, their problem solving requiring one-step tool use emerges especially after the 18th month. Infants not only learn themselves, they also observe their social environment. They observe tool use actions, which is also crucial in their event formation. This observational learning might facilitate their later tool-use. In this section, the role of social learning on tool-related behaviors will be discussed. Firsly, the first signs of prosocial behavior will be critically discussed in section 2.3.1. Afterwards, the constibution of social information on tool-related behaviors will be discussed.

2.3.1. Prosocial behavior

Much of what is known about neonates' prosocial behaviors has been based on studies exploring face perception, biological motion, and gaze following. It remains to determine whether neonates are endowed with some innate knowledge to make sense of the animate world. In section 2.1.1., it was indicated that neonates have the propensity to identify biological motion (Simion, Regolin, & Bulf, 2008) and face-like patterns (Simion & Giorgio, 2015). Spelke and Kinzler

(2007) argue that there is an innate tendency to represent agents, which is not lead by innate tendencies to perceive objects. Beyond these static factors, some researchers have claimed that newborns copy some human facial features, and follow human gazes.

Meltzoff and Moore (1977) demonstrated that newborns can copy some facial features and manual human gestures. Although they call this copying behavior as imitation, it might just be *mimicking* since the goal is not clear (Nielsen, 2006). However, their results have been challenged by some researchers on the basis that those behaviors might be explained by aerodigestive and orofacial development (see Keven & Akins, 2017). Moreover, in a comprehensive longitudinal recent study, Oostenbroek et al. (2016) could not find any concrete evidence that infants in the first weeks are unable to copy neither facial nor manual human gestures. Gaze following is other crucial social behavior, and there is some evidence that newborns (Farroni, Massaccesi, Simion, & Johnson 2004) and 10-to-28-week infants (Hood, Willen, & Driver, 1998) can follow eye gazes; however, it should be noted that these studies suffer from small sample sizes. Systematic evidence that infants can differentiate inanimate objects from humans was presented in a study by Kulmeier, Bloom, and Wynn (2004). They provided evidence that five-month-old infants did not perceive humans as objects. That means, for instance, that they expect self-moving behavior from humans, but not from objects. Based on the *familiarization paradigm*, Woodward (1994; 1998) argue that six- to nine-month-old infants can understand goal-directed behavior of an agents only from seeing their hands. Since these results are all based on simple behavioral patterns, it is necessary to ask about complex action sequences. By the 10th month, infants can understand everyday goal-directed action from a series of events, which means that infants in the first year can parse actions into meaningful units and understand the goal-directed behavior (Baldwin, Baird, Saylor, & Clark, 2001). Here, the crucial point is that the series of events should be *familiar* to the infants. On the other hand, there is a really big prediction here: the very assumption that perception of 'social' events in the early years share the same mechanism with social learning in the later years. This fundamentalist assumption has been extensively criticized by some researchers (see Kagan, 2008).

At the end of the first year, infants already have a strong tendency to follow social markers. Johnson, Slaughter, and Carey (1998) demonstrated that 12-month-old infants are also interested in non-human objects if they have eye-like patterns and they 'behave' *continently*, such as making sounds and moving as if they are giving response to the infants. Furthermore, infants follow the eye-gaze of these non-human objects. These results shed some light on social cognition; if infants at the end of the first year can follow social markers, their attention can be directed by these markers. Thus, there is a gradual increase in keeping action sequences in mind and performing it again (for a review see Meltzoff, 2004).

One of the core studies in the development of social cognition research is Meltzoff's (1988; 1995) cleverly designed imitation study. In this study, a novel action, beyond other action patterns, was demonstrated by an adult, in which the person turned on the light of a light-box with his head. Fourteen-month-old infants imitated the action patterns (one week later) significantly more than control group. Meltzoff (1988; 1995) argued that infants can re-enact the adults' action patterns a long time after it was demonstrated (one week later). These results were replicated by Gergely, Bekkering and Király (2002) in a more recent study. In this study, they created another experimental group of infants and followed the same action patterns (an adult turning the light-box on with their head), but this time the adult demonstrator covered herself with a blanket as if she was cold and she could not use her hands (because she holds her blanket). Surprisingly, infants imitated the adult action patterns one week later significantly more if they were in the hands-free condition compared to hands-occupied (holding the blanket) condition. Gergely, Bekkering and Király (2002) claim that 14-month-old infants' imitation is not simple re-enactment, but rational. Moreover, they argue that infants infer that the demonstrator adult used her head because her hands were occupied. Therefore, they did not imitate their behavior, because the hand of the infants were free. Gergely and Csibra (2003) refer to the inference capacity of infants from goal-directed behaviors as teleological reasoning. Although most of the studies following the Gergely, Bekkering and Király (2002) experiment adhere to the 'rational action' argument (see Sodian, Schoeppner, & Metz, 2004), their results are greatly challenged by an incisively manipulated study conducted by Paulus, Hunnius, Vissers, and Bekkering (2011). Basically, the researchers questioned whether 14-month-old infants really decide not to imitate if the behavior has a rational explanation. Based on the *ideo-motor approach*, which indicates that actions are represented according to the effects of these actions (bidirectional relation between actions and action effects – in other words, sensory consequences) (see Stock & Stock, 2003), and the *motor resonance* literature, which argues that action observation and action execution represented in a common format (Wilson & Knoblich, 2005), Paulus et al. (2011) demonstrated that children imitated the actions which were in their perception-action repertoire. The authors argued that seeing adults' hands near the light-box during training would be the critical factor that triggered the infants to imitate the behavioral pattern due to motor resonance, and *action-effect bidirectional relation*.

The results presented above concerning the imitation capacity of infants before the 16th month could not conspicuously separate imitation from familiarity of actions and motor resonance. In addition, the action pattern had only one step, which was turning the light on with their head. Convincing evidence of whether infants have the capacity to truly understand the goal-directed behavior of the adults beginning with 14 months onwards come from the study by Carpenter, Akhtar, and Tomasello (1998). Using different novel problem tasks that require two action step to solve, they demonstrated that 14-to-18-month-old infants could distinguish accidental actions from goal-directed actions of adults, and reproduce only the goal-directed two-step actions of adults. However, the sample size was only 20, and the age range was too wide; therefore, it might be hard to generalize their findings to all 14-month-olds per se.

Although infants in the second year of life can track people's attention and act accordingly, and infer what might be new for people based on the personal experience of the infant with the adult (Tomasello & Haberl, 2003), to be on the safe-side, it might be better to call the social cognitive capacity of infants before 18 months as prosocial behavior (see Paulus, 2014). Meltzoff (1995) demonstrated that 18-month-old infants could understand the goal-directed behavior of adults with the objects even if the desired goal could not be fulfilled by the adult, and these infants could produce the full action pattern independent of whether the action was fully accomplished by the adult. On the other hand, 18-month-old infants did not ascribe goal-directed actions to mechanical devices. As Tomasello et al. (2005) indicated, this developed capacity to understand the goal-directed actions of others might be closely related to the cognitive development of the self and of understanding others as mental beings as themselves, which will be closely considered in the section 3.2.1. On the other hand, the imitative capacity of infants and the cognitive competence in self-other distinction might be explained by the development of the mirror neuron system (Rizzolatti, Fadiga, Fogassi, & Gallese, 2002; Iacoboni et al., 1999; Rizzolatti, Fogassi, & Gallese, 2001), which is in line with the findings of Paulus, Hunnius, Vissers, and Bekkering (2011) in their research concerning the imitation of pushing the light-box with the head.

2.3.2. From self to other in tool use

> *"As infants' knowledge of themselves expand, they use this new psychological structure as a framework for interpreting others (Meltzoff, 2004)".*

In section 2.2., the bewildering range of competing results from the literature emphasize one fact in their essence: infants are ready to learn tool related behaviors. On the other hand, prosocial and cognitive development make infants ready to learn and solve problems with tools readily. This readiness develops more rapidly in the second year of life (Rat-Fischer, O'Regan & Fagard, 2012). However, there are three critical points: (1) infants are not proficient tool users if they need to use a familiar tool (if the function has been identified as socially, such as a spoon) for a new task (Barrett, Davis & Needham, 2007), (2) they are better at using tools if they need to use it themselves directly, and (3) they have great tendency to learn the use and function of tools socially.

In nearly all the studies discussed in sections 2.1 and 2.2, the researchers show the infants or toddlers how to use the tools or they are shown how to use some tools with their specific demarcated context (like using the spoon only for eating) by their caregivers in their everyday life in a kind of normative way (Casler, Terziyan, & Greene, 2009). This contextual learning of the tools hinders infants and young preschoolers in using the same tool for another problem solving tasks (Barrett, Davis & Needham, 2007; Gardiner, Bjorklund, Greif & Gray 2012). Infants are not able to use a spoon for the problems requiring the use of a spoon except from eating, compared to using a novel tool (Barrett, Davis, & Needham, 2007). That is to say, infants perform better when they use novel tools for novel problem solving tasks. Barrett, Davis and Needham (2007) claim that babies are more flexible, when they use novel tools, but are more fixed for the action patterns of familiar tools. The flexibility issue hinders babies' familiar tool use in new tasks.

Beginning from the first year, infants start to be aware of themselves as intentional beings (see Tomasello, 1999). This may give rise to their better use of self-directed tools than tools directed to the environment or other people around them. Connolly and Dalgleish (1989) underscore that "spoon-to-dish-to-mount cycle" in spoon use may present intentional use of a tool. Researchers have continued to examine whether the more proficient use of some tools (like spoon, comb, etc.) by infants and children is based on whether the self-directedness of the tools is present. McCarty, Clifton, & Collard (2001) show that infants, after 14 months onwards, can adopt grip patterns better with self-directed tools than other directed tools, and particularly more efficiently after 18 months. Results from Claxton, McCarty, and Keen's (2009) study support the idea that 18-month-old children can solve self-directed problems with tools better than other-directed problems. Thus, the question here concerns whether it is a coincidence that researchers persistently emphasize development between 15-24 months of age for proficient tool use problems. As concluded by Claxton et al. (2009) and Rat-Fisher et al. (2012), infants have considerable cognitive changes in this period of their life in terms of solving problems using tools. In Piaget's formulation (1954, 1970, 2003), this period of life presents the step-by-step change from combining tools efficiently with targets to solve basic problems in their environment (stage V) to achieve a mental manipulation of objects (stage VI). As they start to perceive themselves as intelligent beings (Tomasello, 1999), it can be understood why they plan their actions (e.g. adapt their grip patterns with a brush or a spoon) with self-directed tools like spoon.

It has already been shown and discussed that children learn from exploring their environment. They also go beyond the haptic exploration of the environment, and construct affordance relations and make information transfer between different problems, with the help of their developing cognitive capacities in domain general capabilities, such as symbolic development, anticipatory imagery, and hierarchical representations. It is around at the end of their second year that infants solve tool use problems, and in particular, if the problem is self-directed that makes their action plan more precise, this is most probably because they consider themselves to be intelligent beings. However, how does the shift from experiencing themselves as an intelligent being to understanding people's goal-directed actions in sense of tool use happen? The answer concerns the capacity for social learning being crucial in this transition.

2.3.3. Tool use and social learning

2.3.3.1. Clarifying the terms

Before dissecting the relation between social learning and tool use, there are terms should be clarified in order to define social learning: *environmental induction*, *stimulus enhancement*, *mimicry*, *goal emulation*, *result emulation*, *object movement re-*

enactment, *affordance learning*, *imitation and over-imitation*. Some of these terms will be defined based on the tool-use example shown in Figure 7.

Environmental induction is defined as a novel behavior in a group, which resulted from the environmental conditions. Although environmental induction may cause novel behaviors which may be disseminated among the group members, it cannot be considered as social learning (Ramsey, Bastian, & van Schaik, 2007; Nagel, Olguin, & Tomasello, 1993). On the other side, *mimicry* might be the other simplest form of social learning in which just the appearance of the physical stance copied (Zentall, 2006). For instance, Nielsen (2006) states that infants' copying facial gestures of an adult might be the case of mimicry as the goal is not clear. *Stimulus enhancement* is a rather difficult term to interpret. Byre and Russon (1998, p. 668) describe it as "the tendency to pay attention to, or aim responses towards, a particular place or objects in the environment after observing a conspecific's actions at that place or in conjunction with those objects". Thus, it is hard to discuss social learning in that case, since learning is strictly limited to a specified context. Nagell, Olguin, and Tomasello indicate that in stimulus enhancement, "the social environment plays an important role, but the new behaviors themselves are not learned socially, they are learnt individually through the observer's direct interaction with the part of the environment to which its attention has been socially drawn" (1993, p. 174). Although both environmental induction and stimulus enhancement may create novel behaviors among a group which proceeds over time in the social environment, they are not social learning mechanisms. The rest of the terms (types of emulation and imitation learning) are explained with reference to the example given in Figure 7.

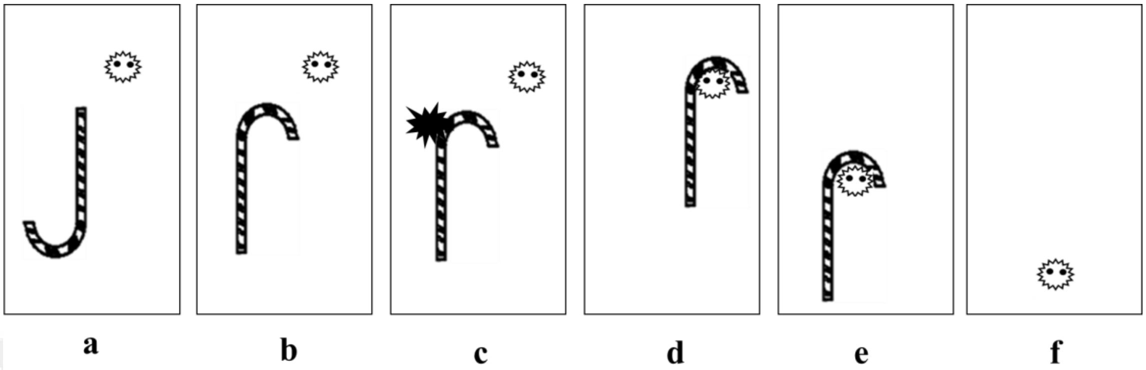


Figure 7: Example sequence of a tool use action demonstrated by an adult.

Figure 7 shows the process through which an adult demonstrates to a three-year-old child how to fetch an interesting toy, which cannot be reached out with hand but requires a tool (a crook). In this task, the crook should be first rotated into an appropriate position in order for it to be used functionally. In this example, the adult rotates the crook clockwise with her fingers (Figure 7b), grabs the rotated crook, and includes a redundant action of knocking the crook on the table (Figure 7c); then, the adult clearly reaches into the distance and hooks the toy (Figure 7d), pulls it toward herself with the crook (Figure 7e), and takes the toy (Figure 7f). The child is given the same crook to copy the actions of the adult. Here are the elements of this task: the tool (crook), the agent (adult demonstrator), the environment (e.g., the table), the target (the toy), action sequence (rotating, grabbing, knocking, reaching out, fetching, and pulling), and the goal (obtaining the toy).

If the child only understands the goal, but does not consider the action sequence, it is called an *emulation*. In this case, the child would try to reach the target without considering the action sequence. Nielsen (2006, p. 555) defines *emulation* as the situation in which “children understand the goal of the model’s action and reproduce the modelled results but do not copy the specific actions used by the model”. However, Whiten, McGuigan, Marshall-Pescini, and Hopper (2009) define two types of emulation: *end-state emulation* and *object-movement re-enactment*. While *end-state emulation* is similar to the definition of emulation indicated by Nielsen (2006) above, they further divide goal-emulation into two categories according to whether only the goal is learnt (*goal emulation*) or the resulting action is learnt (*result emulation*). On the other hand, the reproduced action might only be the body movements of the model. In this case, it is called *object-movement re-enactment*. In the example given above, the child may only copy how the adult demonstrator make the crook move. Another alternative is *affordance learning*. In this case, the child will socially learn only the affordance of the tool, the environment, and the target (Whiten, McGuigan, Marshall-Pescini, & Hopper, 2009). Thus, the reproduced action would be only related to the affordance learning process. However, the child may truly understand the goal of the adult demonstrator and copy only the relevant action sequences without the redundant action (knocking the crook on the table), which is called *imitation*. *True imitation* requires copying the relevant demonstrated actions (Tennie, Call, & Tomasello, 2006). Lastly, *overimitation* means that the child will "reproduce an adult's obviously irrelevant actions" (Lyons, Young, & Kelly, 2007, p. 19751). In our case, it would be copying the action of knocking the crook on the table, which has no connection to the goal.

Social learning mechanisms are not limited to the terms described above. Although there is no agreed definition that can be used to separate social learning from individual *innovation* and stimulus enhancement, some developmental and comparative researchers consider that learned behavior is social learning if the novel behavior is affected by the conspecifics. Nevertheless, as Ramsey, Bastian and van Schaik (2007, p. 395) point out, "the three subsets of novel learned behavior – innovation, environmental induction, and social learning – are not meant to be discrete and mutually exclusive, but instead represent endpoints on a continuum". The literature investigating the interaction among tool use, social learning, and other type of learned behaviors mostly comes from the comparative literature; therefore, the results of the ontogenetic and phylogenetic studies will be presented in tandem through the remainder of this thesis.

2.3.3.2. Social learning in tool use

Although infants at the end of their second year can spontaneously solve one step tool use problems (see section 2.1.), they are not good at solving tool use problems if the solution requires two step action. Nagell, Olguin and Tomasello (1993) demonstrated that while 24-month-old infants imitated the actual process of modeled tool-use action (one step or two steps), chimpanzees focused on the result (emulation). However, if the goal of the experimenter is made clearer, even 16-month-old children can utilize social information in one step tool use problems, which might not be explained by motor resonance and stimulus enhancement (Esseily, Rat-Fischer, O'Regan, & Fagard, 2013). These results show the early development of result learning; emulation. However, the fetching action in these studies would exist in the action repertoire of the infants, which would facilitate *observational learning*. Based on this critique, Esseily, Nadel and Fagard (2010) demonstrated that 18-month-old infants could utilize social information in a multi-step tool-using task. Nevertheless, Nagell, Olguin and Tomasello (2003) and Tennie, Call and Tomasello (2006) underline the fact that unlike emulation, true imitation emerges late; by the 24th month of age. Gardiner, Bjorklund, Greif and Gray (2012) clearly showed how social learning greatly facilitated tool use compared to manual exportation of tools in two-to-three-year-old children. Besides, they point out that performance of two- and three-year-old children in tool use is also dependent on the difficulty of the task. Based on the result of a complex tool-use task, McGuian and Whiten (2009) demonstrated that 18- to 24- and 26- to 35-month-old children focused on the results of the social demonstration, and reproduced only the relevant demonstrated actions. However, older children utilized social information more than younger ones. Similar findings on the role of social learning on two- and three-year-old children were demonstrated by Want and Harris (2001). In their study, it was shown that while two-year-old children's social learning was limited, three-year-old children could select the most efficient modeled action to solve tool-use problem.

To summarize, it can be inferred from these studies that 18-to-24-month-old children are good tool users and social learners. However, it is not possible to reach this conclusion for every aspect of tool-related behaviors since studies in the last decade have repeatedly shown that children are not good at innovating tools, which is the topic of the next section.

2.4. Going beyond using tools: tool innovation and tool manufacture

Last section offers an understanding of tool use and social learning, and the facilitative role of social learning in tool use. In sections 2.2 and 2.3, it was shown that infants in the first year can use self-directed tools such as a spoon, and they can solve means-end problems if the tool and target have a spatial contact and are clearly identifiable. In the second year, infants can adapt their grip according to the goal and inhibit their tendency to use the preferred hand during tool use to solve problems. Although infants are good at solving one-step tool-use problems in the first half of their second year, they are better at solving multi-step tool use problems in the second half of their second year assisted by their developing social learning mechanisms. However, until their eighth year, children have great difficulty in tool innovation. Tool use is an innovative behavior itself, but it is different from tool innovation and tool making as these terms might change according to the context and the species. In this section, first, the term innovation will be clarified. Innovative behaviors are rare among animals, and it is still debated what makes some animals more innovative than others. Most of the literature related to this topic comes from phylogenetic studies. Therefore, the comparative literature will also be summarized and discussed covering the types of innovations, possible reasons for the evolution of innovation, pros and cons of innovative behaviors, frequency of innovation among species, and the relation among innovation, social learning and intelligence.

2.4.1. Behavioral, biological and cultural bases of innovation

2.4.1.1. Innovation defined

One of the most agreed upon definitions of *innovation* is provided by Kummer and Godall (1985, p. 205), who define innovation as “a solution to a novel problem or a novel solution to an old one”. Reader and Laland (2003a, p. 14) present the following comprehensive definition: “Innovation is a process that result in new or modified learned behavior and that introduces novel behavioral variants into a population’s repertoire”. *The process of innovation* (innovation *sensu process*); in other words, how and in which conditions innovative behaviors appear is considered by some to be a purely individual process that needs not be diffused in a group. Following this approach, Ramsey, Bastian, and van Schaik (2007, p. 395) propose the following definition: “Innovation is the process that generates in an individual a novel learned behavior that is not simply a consequence of social learning or environmental induction” (see Figure 8). On the other hand, innovation can be also the end product (innovation *sensu product*), in which there is “a new or modified learned behavior not previously found in the population”

(Navarrete & Laland, p. 243). *Inventions* might be considered as the upper-crust of innovations, which has a high degree of novelty and requires more cognitive effort. Thus, innovation might be a continuum from inventions to *weak innovations* (see Figure 8) influenced by social learning or environmental induction (Ramsey, Bastian, & van Schaik, 2007). Although the emphasized points differ, the definitions of innovations share two core elements: *novelty* and *learning*. Innovations are novel behavioral patterns. For an emergent novel behavior to be considered to be innovation, it must be learned by the animal; in other words, the behavioral pattern must be practiced more than once (Carr, Kendal, & Flynn, 2016; Navarrete & Laland, 2015; Ramsey, Bastian, & van Schaik, 2007). However, as indicated by Ramsey, Bastian, and van Schaik (2007), a novel learned behavior might also simply be the result of social learning. For this reason, if a novel behavior is learned via *observing conspecifics*, it cannot be counted as innovation. Novel behaviors do not only emerge from innovation, social learning and environmental induction; they may also originate from *accidents* or *improvisations*. However, if learning does not occur in relation to the novel behavior, it should not evaluated as innovation (Ramsey, Bastian, & van Schaik, 2007). Additionaly, Chappel et al. (2015) argue that innovations necessitate a specified goal, which also makes it different from *creativity*.

Figure 8: Three main types of novel behaviors according to Ramsey, Bastian, and van Schaik (2007). From "Animal innovation defined and operationalized," by G. Ramsey, M. L. Bastian, C. Van Schaik, 2007, Behavioral and Brain Sciences, 30(4), p. 396. Copyright © 2018 Cambridge University Press. Reprinted with permission.

Innovations vary; for example, they might be eating a new type of food, adopting a new foraging technique, displaying a new type of courtship play or vocalizations, or tool use (Lefebvre, Reader, & Sol, 2004; Sol, 2015; Navarrete & Laland, 2015). For instance, some blue tits and great tits learned how to drink cream via peaking and tearing the foil lids from milk bottles (Fisher & Hinde, 1945), New Caledonian crows and rooks use tools to reach the food (for a review see Chappel, 2006; Seed & Byrne, 2010), and a Japanese macaque learned how to wash potatoes or clean them with other methods before eating (Kawai, 1965). While the *consumer innovations* are simpler (e.g., eating a novel food), *technical innovations* require more cognitive effort (Sol, Sayol, Ducatez, & Lefebvre, 2016; Sol, Griffin, Bartomeus, 2012; Overington, Morand-Ferron, Boogert, & Lefebvre, 2009).

Innovations might have different sources or their emergence might be greatly represented in distinct behavioral patterns. They may first emerge *accidentally* and then be learned by realizing the relation between the accidental behavior and the result. They might also emerge from using *previously learned behaviors for new purposes* or they might be entirely new set of behavioral pattern (Kummer & Goodall, 1985). Based on the human cultural innovations, Muthukrishna and Henrich (2016) categorize the sources of innovations into three aspects: *serendipity*, *recombination* of previous innovations, and *incremental improvement* of technologies, symbols or ideas.

The unassailable differences among the innovations in the animal kingdom leads to other distinctions. Carr, Kendal and Flynn (2016) cluster the types of innovations offered in the literature, and also add their classification based on the difficulty and complexity of innovations. They suggest a triadic from low to mid and high innovations. While the *low innovations* are the unlearned novel behaviors arising by chance, *mid innovations* are novel learned behaviors, in other words individually repeated innovations whereas *high innovations* are those that are both learned individually, but beyond that, must be diffused in a group. The differentiation, between inventions and low innovations, offered by Ramsey, Bastian, and van Schaik (2007) has already been mentioned in the section 2.4.1.1 and represented in Figure 8. A similar distinction has been suggested by Whiten and van Schaik (2007): *cognitively complex innovations* and *cognitively simple innovations*. While the former one requires a deliberate effort towards a goal, the latter one generally stems from an individual discovery at the end of a chance event or exploration. This differentiation between complex and simple innovations are very similar to *passive* and *active innovations* (Rendell, Hoppitt, & Kendal, 2007), and *Type I* and *Type II innovations* (Burkart, Strasser, & Foglia, 2009), respectively.

2.4.1.2. Innovation and evolution: answering the 'why' and 'how' questions?

In the vast literature dedicated to the importance of innovation and its ramifications, there are three underlined topics: evolutionary-ecological, social-cultural and cognitive role of innovations. However, these three topics might work together, making it hard to separate them when explaining the importance of innovations among animal species.

Innovative species are more resilient to environmental changes due to their behavioral plasticity (Sol et al., 2005). Furthermore, innovation increases the chance of survival of the animal by increasing adaptability to the novel environments or allowing animals to find alternative food resources (Sol, 2015; Sol et al., 2005; Sol, Lefebvre, & Rodríguez-Teijeiro, 2005). Innovations may also lead to *macroevolutions*, such that animals may start to have a large role in the designation of their own evolution (Ramsey, Bastian, & van Schaik, 2007; Sol, 2015). Moreover, innovative species might find more food resources to exploit (Sol, Timmermans, & Lefebvre, 2002), and bigger brains to keep track of large territories (for a review, see Lefebvre, Reader & Sol, 2004). Innovative individuals or species that are open to generating novel learned behaviors might also affect the speed of evolution, and finally innovative behavioral patterns or learning novel behaviors might become genetically modified tendencies through mechanisms, such as the *Baldwin effect* (Baldwin, 1986; Simpson, 1953).

Innovation (and also high fidelity social learning) is key to the cultural evolution (Legare & Nielsen, 2015; Tomasello, 1998). There is huge amount of data on the animal behaviors which might be analogical to human culture, and views on this vary drastically. Whether non-human primates and other animals have a culture has been obfuscating researchers for many years (Galef, 1992; McGrew, 1998). Setting aside the discussion on the existence of 'non-human culture', most of the definitions of culture include innovation (McGrew, 1998; Ramsey, Bastian, & van Schaik, 2007; Fogarty, Creanza, & Feldman, 2015). By definition, without an innovator, a novel behavioral pattern cannot emerge. As a result, the innovation might (or might not) spread through the group, which is one of the basic mechanisms of culture (Tomasello, 1999; McGrew, 1998). The co-evolution and culture and the individual learning capacities have been also emphasized with a particular focus on innovation based on the mechanisms of *dual-inheritance theory* (Henrich & McElreath, 2006; Muthukrishna & Henrich, 2016).

In particular, complex innovations and cultural innovations are related with higher order cognitive capacities, such as *high fidelity social learning* (true imitation and/or over-imitation) and *intelligence*. Innovation and intelligence are closely related concepts (van Schaik & Pradhan, 2003), and for some, intelligence is considered as the hallmark of novel behaviors especially in primates (Byrne, 1995; Noble & Davidson, 1996; Parker & McKinney, 1999). However, it should be noted that there is no agreed definition of intelligence, and most importantly, the validity of intelligence tests among animal groups do not show much promise (Deaner, van Schaik, & Johnson, 2006). It is known that innovations are correlated with brain size, and general and social learning capacity (Reader & Laland, 2003a; Reader, Hager, & Laland, 2011). With the help of their advanced cognitive capacities, innovative species might be able to find new solutions to exploit the environment (Reader & Laland, 2001, 2002, 2011; Sol, Timmermans, & Lefebvre, 2002; Griffin & Guez, 2014).

If innovation is that important for animals, then why innovations are rare among animals? Innovations do not only come with pros, there are also cons. Thus, there are two critical points to be discussed: the costs, and frequency of innovations. One of the costs of innovation is related to simple consumer innovations, such as the consumption of poisonous or hazardous foods. Beyond that, there might be a predation risk to innovations. Most of them are cognitively demanding and take time, which might be used for other purposes, e.g., eating, resting, or hiding (Navarrete & Laland, 2015). Additionally, a high level of complex innovation capacity requires bigger brains, and ultimately a very high rate of energy intake (Isler & van Schaik, 2006). Animals which have bigger brains in proportion to their body size (*encephalization*) have longer infancy periods, which makes them open to predation (Ricklefs, 2004). These reasons might explain why innovation rates are low among animals (Navarrete & Laland, 2015). Although most of the innovative species are mammals, there are also highly innovative species among birds (Laland & Reader, 2010). Most of the recorded innovations are from primates (around 75% including chimpanzees, gorillas, and orangutans), and this frequency increases up to 95% if macaques, bonobos and capuchins are added (see Navarrete & Laland, 2015; Lefebvre, 2013; Ramsey, Bastian, van Schaik, 2007).

However, it should be noted that there are many problems in frequency measures, as these measures mostly and highly dependent on the total time of observation and the extent to which the animals' behavioral variety is known (Navarrete & Laland, 2015; Lefebvre, 2011). Hunt and Gray (2007) and other researchers (see Emery & Clayton, 2004) argue that the 'primate oriented view' in the innovation literature heavily impinges upon the definition, observation and identification of innovations, and disregard the literature from birds, especially from the corvid family.

Concerning how innovation capacity evolved, there are different, and sometimes contradicting, views on why innovation is frequent in some species but infrequent in others. Probably, there is not only one answer to this question, since innovativeness might be an *exaptation* than adaptation. In other words, innovativeness might emerge as a combination of factors (Sol, 2015). Innovativeness is high in *semi-terrestrial* animals, such as chimpanzees (*Pan troglodytes*), compared to *arboreal* species (Meulman, Sans, Visalberghi, & van Schaik, 2012). Complex innovations might especially require a high degree of manipulative capacity so that the *morphology* of limbs (e.g., freed hands) has a crucial role in manipulating tools (Navarrete & Laland, 2015). In addition, innovativeness requires some degree of control over emotional responses; in other words, 'endocrine control mechanism', which is related to the control of emotional responses in stressful conditions; e.g., exposure to a novel environment or novel objects (Rickfels & Wikelski, 2002). Some animals have a high level of *neophobia* (Greenberg, 2003). These animals do not approach novel objects or have an aversion to trying new food (Sol, Griffin, & Bartomeus, 2012; Sol, 2015). Neophobic animals are unlikely to be innovative (Webster, & Lefebvre, 2001); however, neophobia can be crucial for the survival of some animals. Animals which exhibit *neophilia* are more innovative species (Greenberg, 2003); they are opportunist feeders (consumer innovation) or have a high degree of innovativeness (Griffin, Netto, & Peneaux, 2017; Sol, Griffin, Bartomeus, & Boyce, 2011). *Motivation* is another factor that also related to neophobia and neophilia. According to Sol (2015), motivation is probably "driven by hunger and affects innovation latency by favoring *exploration* and persistence in trying to solve a problem". As motivational factors, *curiosity* and *exploration* (*play* as a main mechanism) have also been underlined in childhood innovations as a contributor factor by Carr, Kendal, and Flynn (2016) and Riede et al. (2017). One of the other reasons might be slow *life histories*, such as prolonged infancy and a longer life expectancy. Animals which have longer lives also have higher innovation rates

(Lefebvre, Whittle, Lascaris, & Finkelstein, 1997; Reader, Hager, Laland, 2011; Overington, Morand-Ferron, Boogert, & Lefebvre, 2009; Sol, Sayol, Ducatez, & Lefebvre, 2016). At this juncture, the utmost result from the evolution of innovativeness literature is that innovation and *brain size* are positively and highly correlated (Lefebvre, Whittle, Lascaris, & Finkelstein, 1997; Reader & Laland, 2002).

Brain size is a very significant predictor of general learning capacity in mammals after the body size is controlled (Navarrete & Laland, 2015; Roth & Dicke, 2005). To decipher the very important and complex relation between brain size and innovations, first the reason why the brain has become bigger in primate lineage should be considered. There are four prominent hypotheses on the evolution of brain size and intelligence in primates and homo line in the evolutionary history: 'Ecological-intelligence', 'social intelligence', 'cultural intelligence', and 'technical intelligence' hypothesis. The *ecological-intelligence hypothesis* (Rosati, 2017; Clutton-Brock & Harver, 1980; Gibson, 1986) emphasizes the enlargement in the brain size in primate evolution as a response to ecological changes and non-social factors, such as finding food and foraging. In contrast, the *social-intelligence hypothesis* (Humprey, 1976; Byrne & Whiten, 1988; Dunbar, 1998; Kamil, 2004; Dunbar, & Shultz, 2007; Whiten, in press) proposes that intelligence and brain size increase to manage complex social relations; for instance, making coalitions or allies, following social cues, manipulating others to gain rewards. The *cultural-intelligence hypothesis* (Herrmann et al., 2007, p. 1360) asserts that "participating and exchanging knowledge in cultural groups" created a selection pressure; thus, gave direction to the evolution of intelligence (also see Moll & Tomasello, 2007). However, a recent computational-model based study indicates that the brain size of Homo sapiens is better predicted "when individuals face a combination of 60% ecological, 30% cooperative and 10% between group competitive challenges, and suggests that between-individual competition has been unimportant for driving human brain-size evolution" (González-Forero & Gardner, 2018, p. 554). Finally, the '*technical-intelligence hypothesis*' (Byrne, 1997) highlights the behavioral organizations required to execute activities requiring a high number of sequential activities, such as tool making. Selection pressure might have favored the species that could manage a high number of sequential activities, which leads to a higher level of intelligence. Whatever perspective is adopted, innovation has a crucial role in all these perspective, because ultimately, the plasticity of behavior in foraging, feeding, or any other behavioral or consumer innovation demands bigger brains.

Returning to the relations among innovation, different types of learning mechanisms and brain size, there has been an abundance of studies that have investigated these relations from different perspectives. As mentioned above, there is a positive link between innovation rate, social learning capacity, and brain size (Reader & Laland, 2002). Supportive evidence comes from studies that have demonstrated a correlation between encephalization and innovation rate in mammals, particularly in primates or the homo line, and brain size and innovativeness in birds (Lefebvre, 2013; Reader & Laland, 2002; Reader, Hager, & Laland, 2011; Overington, Morand-Ferron, Boogert, & Lefebvre, 2009; Lefebvre, Whittle, Lascaris, & Finkelstein, 1997; Sol et al., 2005).

The relation between innovation and brain size can be two-sided (Navarrete & Laland, 2015). Larger brains might have evolved for reasons other than innovation and social learning, but finally contributed to them as these capacities requires high level of information processing that can be undertaken with the help of a high volume of neurons (Wilson, 1991). However, innovativeness might have created a selection pressure on some species, thus the enlargement of the brain size (Reader, Hager, & Laland, 2011; Reader & Laland, 2002). Nevertheless, mere innovation capacity might not be sufficient. For innovations to spread through a group, other members of the group need to learn from their conspecifics. Social learning and innovations are the leading engines of culture, indeed (Legare & Nielsen), as stated above. It is known that group size and brain size are correlated in the homo line (Dunbar & Shutz, 2007) and social learning, innovativeness and brain size are correlated (Reader & Laland, 2002). These results seems to suggest there are domain general intelligence mechanisms related to brain size, which resulted in increased behavioral plasticity and innovativeness, and the capacity for social learning (Lefebvre, 2013; Reader, Hager, & Laland, 2011). However, a conceptual conflict exists. High fidelity social learning requires the copying the behaviors of conspecifics; therefore, there is little space for innovation in high fidelity social learning. Although intelligence, social learning and innovation might be related at a species level, namely innovation as a sensu product (Reader & Laland, 2002), a strong correlation might not be expected between innovation and social learning among individuals in a group (Reader, 2003). Following this line of reasoning, it is relevant to consider the findings of Muthukrishna, Morgan and Henrich (2016) and Osiurak et al. (2016), which suggest that there is a negative relation between intelligence and social learning, and the predictive power of social learning is lower than technical intelligence in the cumulative cultural innovations in human adults. However, some species are more innovative when they are separated from their group (Griffin, Lermite, Perea & Guez, 2013). All these results demonstrate that an intricate relation between innovation and social learning. Nevertheless, there are many questions that need to be answered before stating succinctly that social learning and innovation are related and they might be based on general intelligence.

Although there has been an extensive discussion of the findings related to the evolved capacities for innovative species or innovativeness, as yet it has not been considered who the inventors in a group or a species are, and what make them the inventors, namely the factors affecting innovations in a group and individual differences in a group. Innovations are not only rare among animal species, but also innovators are rare in same-species groups. A Japanese macaque monkey, Imo, was very talented in finding new techniques for foraging and eating (Kawai, 1965). Betty, a New Caledonian crow, could manipulate a novel tool to extract food that she could not reach without the tool (Weir, Chappel, & Kacelnik, 2002). There were only a couple of individuals that exhibited innovative tool use among macaques (Comins, Russ, Humbert, & Hauser, 2011; Leca, Gunst, & Huffman, 2010). As Navarrete and Laland (2015, p. 254) commented, “Individuals capable of inventing solutions to new challenges, or exploiting the discoveries and inventions of others, may have had a selective advantage over less able conspecifics.” Based on the extensive literature of the published data on the behaviors of primates, Reader and Laland (2001) demonstrate that there are three main indices of the innovators: social rank, age, and sex. There are more male than female innovators. However, this might be related to the “female-biased sex ratio in the populations” (Navarrete & Laland, 2015, p.245). Low-rank primates were more innovative than high rank individuals. Besides, mature primates were more innovative than young ones (Reader & Laland, 2001). As discussed in the previous paragraphs, there are some cognitive processes involved in innovation rates. Individual differences in cognitive capacities affect innovativeness, such that individual with higher cognitive capacities tend to have higher innovation rates (Reader, 2003). The length of life and their foraging ecology might be other factors that could affect the innovators in birds and primates (Sol, 2015; Sol, Sayol, Ducatez, & Lefebvre, 2016; Greenberg & Mettke-Hofmann, 2001; Boogert, Reader, Hoppitt, & Laland, 2008). On the other hand, innovators tend to have divergent personalities in their group [see the editorial of Reader and Laland’s (2003b) book for more information].

In summary, innovativeness is affected by different factors, and it is unlikely that there might be one underlying evolved mechanism. Innovativeness depends on the ecology of the species, body morphology, brain size, and many other factors related or unrelated to these factors. Species exhibiting innovative behaviors are rare, and innovators are also rare in the same-species group. Although brain size and consumer innovations are positively related, consumer innovations are simple and they are mostly affected by the biological tendencies of animals. Most consumer innovations are considered to be simple innovations. However, innovations related to tools are complex; that is, they are cognitively demanding. The later sections and chapters will focus on complex innovations, in particular, innovative tool use and tool making.

2.4.2. Technical innovations in animals

So far, innovation has been considered as a comprehensive term emphasizing novelty and learning. However, some innovations are cognitively more demanding, as indicated in sections 2.4.1.1 and 2.4.1.2. *Technical innovations* are complex innovations, and they are classified including different types of tool use (see Overington, Morand-Ferron, Boogert, & Lefebvre, 2009). Here, and in the remainder of this thesis, two types of these technical innovations will be discussed: the *innovation of new behavioral techniques* and *tool innovation*. Examples from birds (mainly corvid family) and primates (mainly chimpanzees) will be presented. As shown in the bewildering literature of tool use and innovation, the physical cognitive abilities of birds and primates are comparable (Seed & Byrne, 2010; Taylor, 2014). Nevertheless, cognition might have occurred convergently (*convergent evolution*) in birds and primates (Reader & Laland, 2002). Eschewing the discussion on the origins of cognition in birds and primates, the results of the technical innovation studies from both birds and primates will be addressed, focusing primarily on the task used in these studies. Therefore, first, what tool innovation means will be defined and studies from non-human animals will be summarized including the descriptions of the tool innovation tasks used in these studies. Then, studies on the tool innovation and tool manufacturing capacity of children will be reviewed.

2.4.2.1. Innovation of new behavioral techniques and causal reasoning

The innovation of new behavioral techniques requires using new behavioral patterns or merging familiar but distinct behavioral patterns to solve novel problems. These tasks mostly necessitate determining the physical demands of the task.

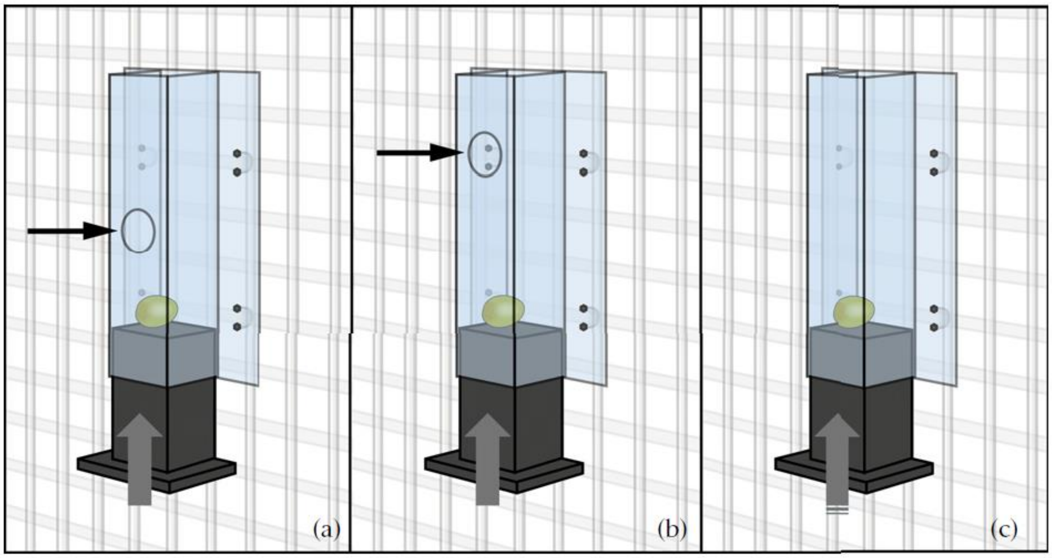


Figure 9: The puzzle box used by Manrique, Völter and Call (2013, p. 197): Apparatus 1 (a), apparatus 2 (b) and apparatus 3 (c). From "Repeated innovation in great apes," by H. M. Manrique, J. C. Völter, J. Call, 2013, Animal Behaviour, 85(1), p. 197. Copyright © 2018 Elsevier. Reprinted with permission.

One example of innovation by means of using new behavioral patterns to solve a novel problem is contained in the study by Manrique, Völter and Call (2013). In this study, they used a puzzle box to reveal innovation via inhibiting previously learnt responses in captivate great apes (see Figure 9). The apparatus was a long transparent rectangular box attached to the apes' cage. The lower part of the apparatus had a piston that could be pushed upwards, and the upper part was open. Inside the transparent box was a grape place on the upper part of the piston. There was a hole in the box (on the side facing the subject) either close to the grape in apparatus 1 or far from the grape in apparatus 2. There was no hole in apparatus 3. While the subjects reach the grape using their finger in the first apparatus (fingering technique), they needed to push the piston upwards and to take the grape with their finger (lifting technique) or for the second apparatus, they had to hit the pistol with force, which would make the grape shoot through the opening at the top of the box (shooting technique). For the last apparatus, the ape could only gain the reward with the shooting technique (see Figure 9). Although all the subjects were presented with the apparatus in the same order (from apparatus 1 to 3), chimpanzees, bonobos, and gorillas could inhibit their previously learnt techniques (lifting or fingering) and innovate the most complex solution, e.g., lifting technique in the second apparatus or shooting technique in the last apparatus). Unlike other apes, the orangutans were not innovative, and this result contradicts the claim of van Schaik et al. (2015) in that captive orangutans might be innovative in captivity. However, orangutans could succeed in some innovation tasks that require the use of familiar tools for novel problems (see Mendes, Hanus and Call, 2007), and this will be further described in the next section. Returning to the study of Manrique, Völter and Call (2013), this study exemplifies that most of the great apes can innovate new behavioral techniques to solve novel problems by means of inhibiting previously learnt strategies. Likewise, their result may also indicate that most of the great apes can conceive the *causal* relation between the physical force and the grape by means of understanding the functioning of the apparatus, which could be an indicator of *insightful learning*. However, another interpretation could be that it is the *perceptual-motor feedback* (see Taylor et al., 2010) from the movements of the grape that the subjects obtain whenever they use the piston; thus, finally the subjects press the piston more and more based on the jumping movements of the grape until they discover and learn the function of shooting. This view has greatly challenged the insightful learning view (Shettleworth, 2009; Taylor et al., 2010; Taylor, Knaebe, & Gray, 2012; Seed & Boogert, 2013). Additionally, it may not be the case that great apes understand the unobservable causal relations (see Penn & Povinelli, 2007), but learn it through trial-error and perceptual-motor feedback. For instance, chimpanzees have great difficulty in solving *trap-tube* problems (see Figure 10 for an example) in which subjects need to avoid pushing the reward into the dead end that is in the middle of a horizontal plastic tube while fetching the reward with a long stick, in other words, understanding the force of gravity (see Povinelli, 2000). Three-year-old human children can solve trap-tube problems after some experience and trial-error (Visalberghi & Tomasello, 1998), and by the age of six years old, children can solve trap-tube problems even without a social demonstration (Horner & Whiten, 2007). These results would indicate that chimpanzees may not have a physical understanding of gravity, which necessitates engaging in abstract reasoning about the causal relations that are not visible. Surprisingly, non-tool-using rooks (Tebbich, Seed, Emery, & Clayton, 2006) and New Caledonian crows (Taylor, Hunt, Medina & Gray, 2009) can solve trap-tube problems. Rooks are particularly interesting in this case, because they do not use tools in the wild unlike New Caledonian crows (Hunt & Gary, 2004; Rutz, & Clair, 2012). Beyond that, some birds are surprisingly innovative in finding solutions for the tasks that requires behavioral flexibility, such as keas and New Caledonian crows (Auersperg et al., 2011).

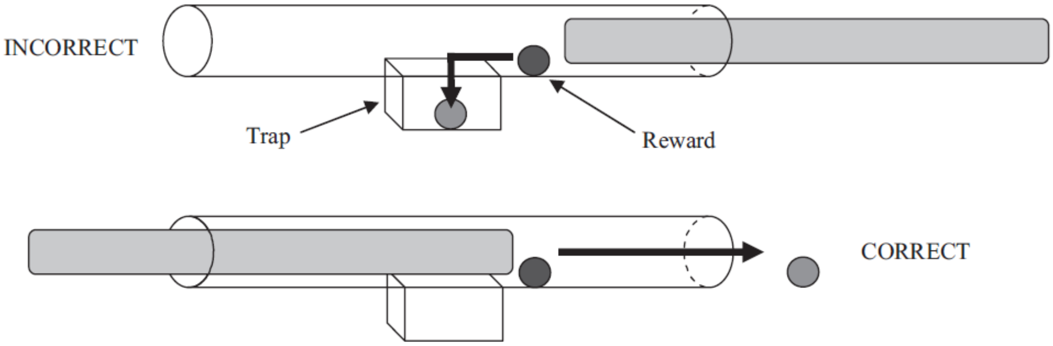


Figure 10: Trap-tube problem. From "Learning from others' mistakes? Limits on understanding a trap-tube task by young chimpanzees (*Pan troglodytes*) and children (*Homo sapiens*)," by V. Horner, and A. Whiten, 2007, Journal of Comparative Psychology, 121(1), p. 13. Copyright © 2018 Elsevier. Reprinted with permission.

The innovation of new behavioral techniques might also be required to merge previously learnt actions in order to solve a new problem. Promising examples for this kind of innovation come from the metatool use paradigm, in which multiple steps are required to solve a tool related problem. Taylor, Hunt, Holzhaider, and Gray (2007), and Taylor, Elliffe, Hunt and Gray (2010) familiarized New Caledonian crows to different one-step tasks that needed to be solved by using a single tool given or by just making a single action step, such as using a long stick to extract the food from a long horizontal tube or pulling on a long string to get the meat which had tied to the far end of the string. Afterwards, New Caledonian crows were presented with a novel metatool problem (see Figure 11). The results demonstrated that New Caledonian crows can merge the action patterns that they learnt in different context for novel three step problems. Subjects could (1) pull on a string to obtain a small stick that was tied to the end of the string, (2) use this stick to fetch a long tool inside a tool box (the long stick could not be reached without a stick), and (3) use the long stick to retrieve the bait (meat) inside a long hole. Taylor et al. (2010) argue that New Caledonian crows' ability to solve metatool use problems go beyond simple chaining, as they need to combine familiarized single action steps into a novel multi-step tool use task. This ability to sequence actions according to a goal might show their ability to construct *hierarchical representations*. Cautiously, it could be stated that some bird species (especially the corvid family) may have better abilities for making non-visible connections, such as causal chains and/or structuring actions according to a goal, than some non-human primates (see Kacelnik, 2009; Chappell, 2006; Lambert et al., 2017; Emery & Clayton, 2009; Auersperg et al., 2011; Seed, & Byrne, 2010). However, as Wimpenny et al. (2009; p. 1) highlight, "seemingly intelligent behavior can be achieved without the involvement of high-level mental faculties, and detailed analyses are necessary before accepting claims for complex cognitive abilities".

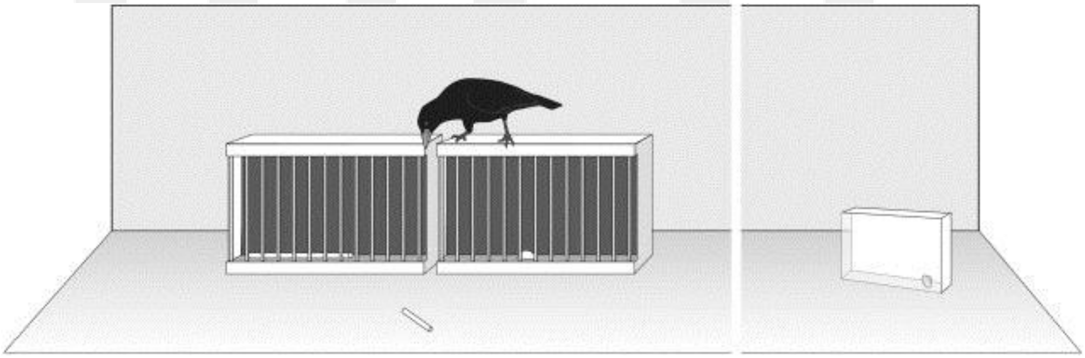


Figure 11: Metatool use problem. From "Spontaneous metatool use by New Caledonian crows," by A. Taylor, G. R. Hunt, J. C. Holzhaider, and R. D. Gray, 2010, Current Biology, 17(17), p. 1505. Copyright © 2018 Elsevier. Reprinted with permission.

2.4.2.2. Tool innovation

One of the most common innovation types that have received the attention of researchers over many years are those innovations that require using tools (Navarrete, & Laland, 2015). Tool innovation is a type of behavioral innovation that is formulated in the physical realm and necessitates using a tool or tools (Carr, Kendal, & Flynn, 2016). Tool innovation can be classified into two aspects:

(1) new ways of using familiar tools or (2) new methods of tool construction for novel problems. The latter one is the rarest, and is the main subject of this thesis.

2.4.2.2.1. USING FAMILIAR TOOLS IN NOVEL WAYS: FLOATING PEANUT TASK AND AESOP'S FABLE

Innovation by means of finding new ways of using familiar tools for novel problems has been extensively investigated in primates and birds. The most common task is the *floating peanut task* (Figure 12), or another version of the task which is called *Aesop's fable* (Figure 13).

As above, captive orangutans are not good at finding new techniques to solve a novel problem via inhibiting prepotent responses (Manrique, Völter and Call's (2013). However, these results would be task-specific and captivate orangutans might be innovative unlike their wild cousins (van Schaik et al., 2016). A study by Mendes, Hanus and Call (2007) presented captive orangutans (*Pongo abelii*) with a long transparent vertical tube attached to their cage. One quarter of the tube was filled with water, and there was a peanut floating inside the tube. The solution to the task was to add water (which normally functioned as a source of drinking water thus a familiar 'tool') to the tube until the peanut can be reached with fingers. Surprisingly, all five of the orangutans used water in a novel way in the first trial after seeing that the reward could not be reached; e.g., with fingers. They collected water from the water dispenser and spat it into the tube until they were able to retrieve the peanut with their fingers (See Figure 12). Mendes et al. (2007) interpreted these results based on insightful problem solving. However, as the orangutans were experienced in using the dispenser, further research needs to be conducted with naive orangutans. Nevertheless, the results are promising and show the contribution of *planning* and *imagination* in ape, but the possible effect of perceptual-motor feedback should be clarified in future studies (Taylor & Gray, 2009).

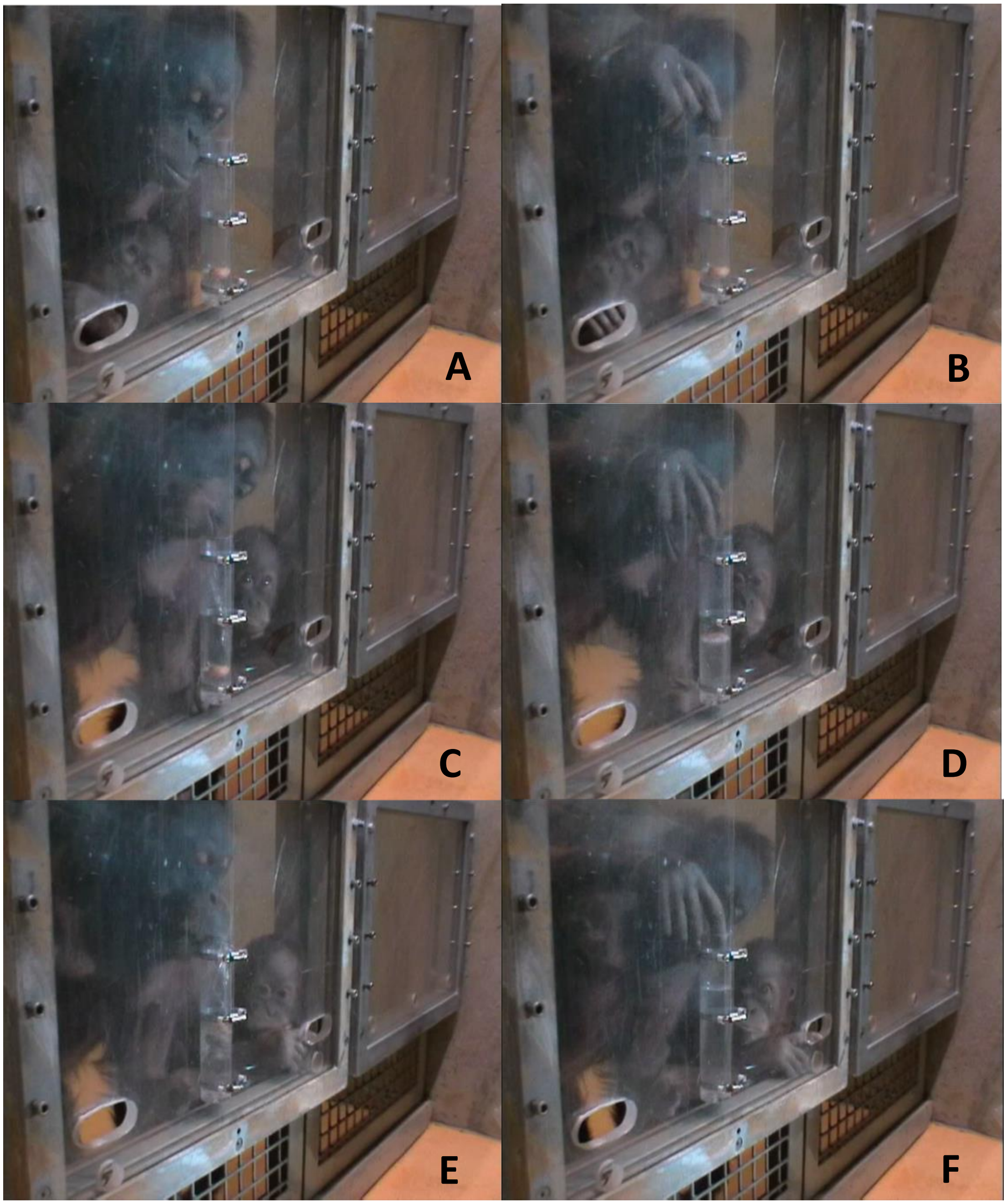


Figure 12: Floating peanut task. The orangutan spits water inside the horizontal tube in order to reach the peanut via raising the water level. Letters indicate the sequence of events according to time. From "Raising the level: orangutans use water as a tool," by N. Mendes, D. Hanus, and J. Call, 2007, Biology Letters, 3(5), supplemenary video. Copyright © 2018 Royal Society. Image stills are taken from the video with permission.

In another study, Hanus, Mendes, Tennie and Call (2011) tested gorillas (*Gorilla gorilla*), chimpanzees (*Pan troglodytes*), orangutans (*Pongo pygmaeus*), and human children (*Homo sapiens*[1]) in a series of experiments comparing the floating peanut task with a different group of apes in each experiment. In Experiment 1, none of the captive chimpanzees and gorillas could solve the task. This was surprising, because chimpanzees are known to be capable innovators (Kummer & Goodall, 1985). In Experiment 2, they tested orangutans and chimpanzees living in a sanctuary using dry (the tube was dry) or wet (the tube was filled with some water) conditions. Only a few of chimpanzees (5 out of 24) were able to solve the task and three were in the wet condition, whereas none of the orangutans could solve the task. Furthermore, only one of the chimpanzees solved the problem in the first trial. In Experiment 3, the researchers tested most of the chimpanzees that had participated in Experiment 1 and three new chimpanzees, but with a new water dispenser [because the water dispenser used in Experiment 1 had previously been mounted on the cage, and chimpanzees had only used it to access drinking water whereas in the original study, Mendes et al. (2007) mounted a new water dispenser close to the task]. They compared results of the chimpanzees in the first and second experiments. Although success rates between the new and old dispensers did not significantly change, there was a difference between groups in the spitting behavior. The results of Experiment 4 (with human children) are discussed in section 2.4.3. In the light of these results, it should be noted that it is hard to reach a conclusion from only a handful of studies. We should learn more about the animals in terms of their anatomy to utilize tools, nature of the behavior in the wild, the context and familiarity with the task components including action components required to solve the task, and species differences.

A similar version of floating object task is *Aesop's fable*, based on a story about a crow dropping stones into a pitcher in order to raise the water level inside the pitcher, for the crow to drink (for an example, see Figure 13). While water was used as tool in floating object task, stones were required to solve tasks based on the paradigm of Aesop's fable. This task was first developed by Bird and Emery (2009a, 2009b) to measure the tool innovation abilities of rooks (Figure 13). There were four rooks that were able to solve the Aesop's fable; that is to say, they dropped enough number of stones to obtain a worm floating on the water (Figure

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[1] Unfortunately, other species of *homo* line have extinct!

11a). In a second experiment, Bird and Emery (2009b) demonstrated that rooks quickly learned the function of larger stones over smaller stones and used larger stones significantly more often over several trials. In the third experiment, they found out that subject added significantly more stones into the tube containing water compared to the tube containing sawdust (Figure 13b). Not only non-tool-using rooks, but also other members of the corvidae family passed the test, such as crows (Taylor et al., 2011) and Eurasian jays (Cheke, Bird & Clayton, 2011). However, seeing the rising water level is a perceptual-motor feedback for the members of the corvidae (Clayton, 2015), unlike human children who can simulate their action results in the same task (Miller et al., 2017).

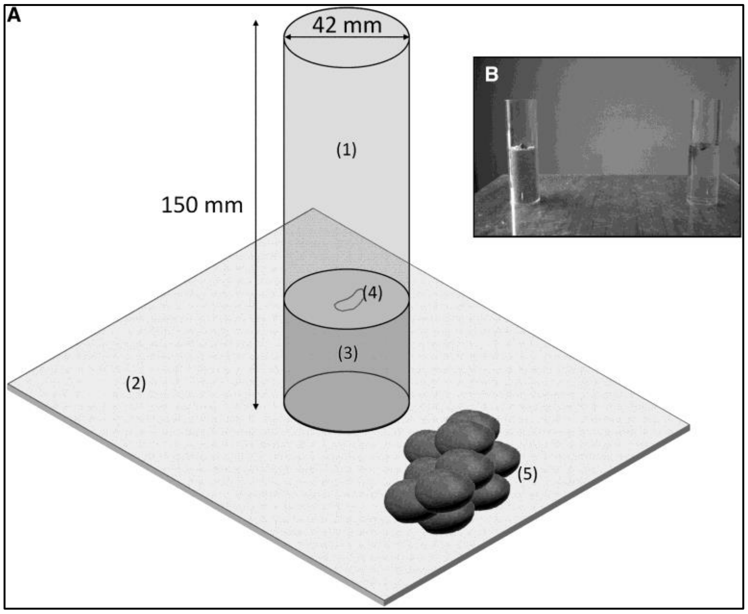

Figure 13: A task based on Aesop's fable paradigm. A represents the setup of the first and second experiment, and B represents the setup of the third experiment of Bird and Emery (2009b). Numbers represent the (1) transparent tube, (2) transparent Perspex surface, (3) water, (4) worm, and (5) a pile of stones, respectively. From "Rooks use stones to raise the water level to reach a floating worm," by C.D. Bird, and N. J. Emery, 2009b, Current Biology, 19(16), p. 1411. Copyright © 2018 Elsevier. Reprinted with permission.

2.4.2.2.2. INNOVATION VIA CONSTRUCTING OR FASHIONING A TOOL: TOOL MAKING

In the wild, chimpanzees commonly use tools as they are without making any modification, which is easier than fashioning tools, and it is rare that chimpanzees change the shape of tools according to the demands of the task. For instance, Boesch and Boesch (1990) indicate that only 30% of observed tool-use behaviors in Thai chimpanzees include changing the shape of the tool. More critically, they often make tools with less rigid materials (e.g., sticks) than more rigid materials (e.g. stones); nevertheless, frequency of the raw material in their ecology affects the selected material as expected. There are clear examples of tool making in chimpanzees, such as ant dipping and nut cracking. In the former action, chimpanzees can make tools to collect ants from their nests. To do this, they find an appropriate raw-material (e.g., twig), pull the leaves from the twig, chop the twig into the right size with their teeth, insert the twig into the ant nest, wait until some ants climb on the twig, remove the twig, and collect them with their fingers or lips. The shape of the twig might change according to the size of the nest or even type of the ant (Humle & Matsuzawa, 2000; Boesch & Boesch, 1990). Another example is nut cracking in which groups of chimpanzees can select an appropriate stone and modify it in a way that it can be used to crack the target nut (Boesch & Boesch, 1990; Morgen & Abwe, 2006; Sanz & Morgan, 2007). Chimpanzees' ability to use and make tools is impressive, although their capacity to manipulate tools is limited when compared to humans and they mostly innovate solutions which are already in their motor repertoire. Tennie, Call and Tomasello (2009) argue that such behaviors (tool making for ant-dipping or nut cracking) are probably invented by gifted chimpanzees independently and spread into the group slowly, mostly by simpler learning mechanisms, such as stimulus enhancement or result emulation. They refer to the chimpanzee's capacity to invent solutions, such as '*zone of latent solutions*'. There is evidence from observational and captivity studies; for instance, nut cracking is observed in different chimpanzee groups which do not have interactions (Boesch & Boesch, 1990; Morgen & Abwe, 2006; Sanz & Morgan, 2007) or the innovative tool-related behaviors observed in the wild could be invented by naive chimpanzees (Bandini, & Tennie, 2017). Tool innovation via fashioning or constructing a tool is rare, probably because it requires both innovative behavioral modifications, tool use, and controlled tool making. This type of innovation is very difficult for non-human apes and preschool children (Tennie, Call, & Tomasello, 2009; Price, Lambeth, Schapiro, & Whiten, 2009; Beck et al., 2011). The following paragraph gives the details of three tasks using loop, hook, and composite tools, in which the rigidity of the tool increases respectively.

Based on the *zone of latent solutions* argument, Tennie, Call, & Tomasello (2009) introduce the loop task in which its solution might not exist in the innovative repertoire of great apes (chimpanzees, gorillas, orangutans, and bonobos) and four-year-old human children. In this task, there is a plastic platform with a protruding screw mounted on it. There was also some bait on the platform. The platform was in a mesh-box, and the protruding screw was close to the front side of the box, in which a subject could see easily but not reach with the finger. The subjects were given a piece of long straightened wood wool that was moistened to be more flexible. If the subject was able to fashion a loop with the wood wool, insert it through the mesh, and loop it over the screw, they could pull the platform toward themselves (see Figure 14). None of the subjects could solve the task spontaneously, but most of the children were able to solve it after the social demonstration. The performance of the children will be discussed in section 2.4.3.

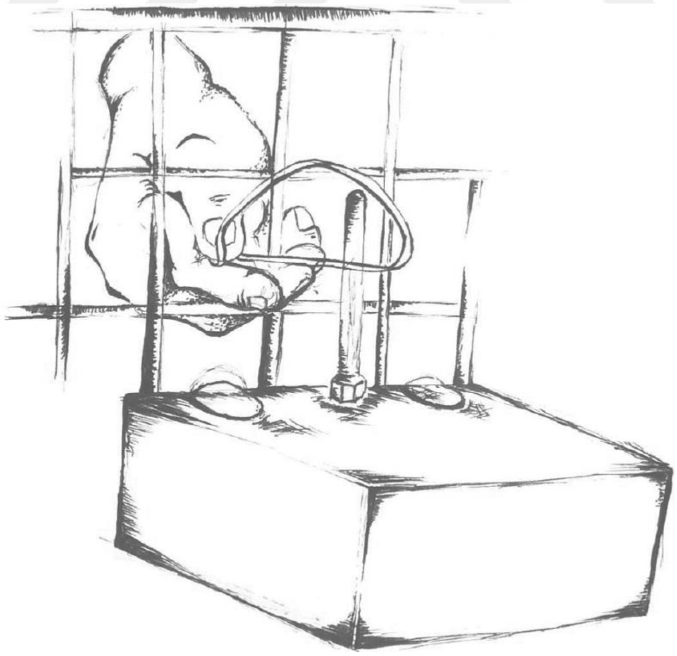

Figure 14: The loop task. From "Ratcheting up the ratchet: on the evolution of cumulative culture," by C. Tennie, J. Call, and M. Tomasello, 2007, Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1528), p.2410. Copyright © 2018 by the Royal Society. Reprinted with permission.

If there is an animal that can challenge many theories in comparative studies, it would be birds, especially the crows, and particularly the New Caledonian crow. This type of crow uses and makes tools; e.g., hooks from twigs to catch the prey from tree hollows, in their natural ecology (Hunt, 1996; Hunt & Gray, 2004). Weir, Chappell, and Kacelnik (2002) designed the hook task to measure the physical problem solving abilities of New Caledonian crows. In this task, there is a vertical long tube, and inside this tube is a small bucket containing the bait (Figure 15). The subjects were given a piece of wire. To complete the task, it was necessary to bend the wire and use it to hook the bucket, then pull it out from the tube in order to obtain the bait. The task was solved by one of the New Caledonian crows named Betty, and it was to this bird that Alexander Allan Scott Weir dedicated his PhD thesis (Weir, 2005).

There is ample evidence that New Caledonian crows have the ability to use and make tools, and it is not task-specific or tool-specific. They can bend or unbend tools according to the target task and select the most appropriate tool (Chappell & Kacelnik, 2002; Weir & Kacelnik, 2006). Furthermore, New Caledonian crows do use tools in the wild, therefore, it is under debate whether their ability to use and make tools is based on a specified evolved *domain-specific physical problem solving mechanism* (henceforth, *physical intelligence*) or *domain-general problem solving mechanism* (henceforth, *general intelligence*). Evidence that this ability might be actually based on an evolved general intelligence mechanism comes from non-tool using birds, such as rooks. Bird and Emery (2009) demonstrated that non-tool-using rooks can actually solve the hook problem by constructing a hook shape from a piece of wire. However, it should be noted that in all these studies, rooks or New Caledonian crows already used and/or had seen hooked materials. Further evidence came from Goffin's cockatoos, who are able to detach slivers of wood from logs and use these pieces to reach food (Auersperg et al., 2012). The details of the hook task will be further discussed in the following sections and chapters.

All the tasks introduced in this section and section 2.4.2.2.1 required a tool to be used as is, to remove some parts to from the main raw material, or to change the shape of one tool. For example, the loop task and the hook task simply required to change the shape of one tool. However, composite tool construction is very rare even among chimpanzees (Matsuzawa, 2001). These technologies take time to spread taking thousands of years for them to accumulate, and they require higher cognitive demands (Ambrose, 2010; Wadley, 2010). Price, Lambeth, Schapiro and

Whiten (2009) demonstrated that chimpanzees could not combine two sticks to obtain far away bait that they could not reach with their hand unless they had watched their conspecific's full action demonstration of combining two sticks to reach the bait with the constructed stick.

To summarize, technical innovations are rare among species, and tool-related technical innovations are even rarer. Some animals can use familiar tools or construct/fashion tools to solve novel problems. Sections 2.2 and 2.3., revealed that children in the second year of their lives use tools, and in the third year, they can easily solve novel one-step tool related behaviors. However, children cannot innovate tools spontaneously until they are seven to eight years old, and this raises the question of what makes tool innovation (excluding one step behavioral innovations) particularly difficult for pre-school children. Therefore, the next section will focus on the literature investigating the development of tool innovation in children.

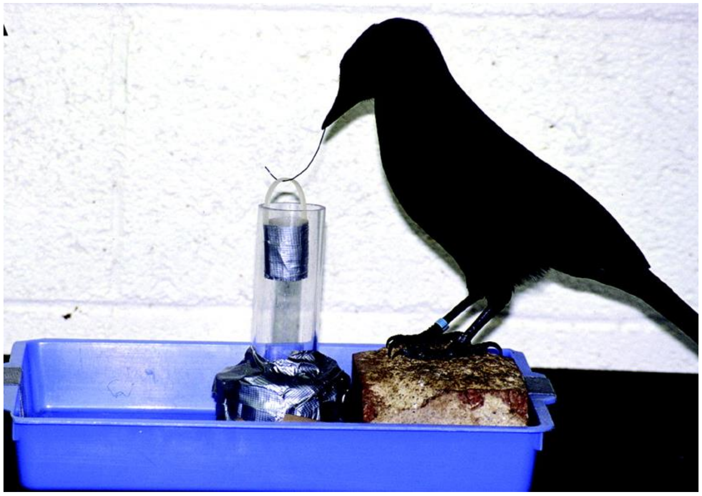

Figure 15: Hook task and Betty. From "Shaping of hooks in New Caledonian crows," by A. A. Weir, J. Chappell, and, A. Kacelnik, 2002, Science, 297(5583), p.981. Copyright © 2018 by The American Association for the Advancement of Science. Adapted and reprinted with permission.

2.4.3. *Tool innovation in children*

Innovative use of familiar tools and novel tool making does not appear in the early years of human life (Cutting et al., 2011; Mounoud, 1996), although the motor and cognitive capacities for tool innovation originate in early tool use behavior (Nielsen et al., 2014; Legare & Nielsen, 2015). Even in the first year of life, infants start using tools, such as a spoon (Connolly & Dalgeish, 1989) or make causal means-end relations between a tool and a target; e.g., fetching an object with a tool (Bates, Carlson-Luden, & Bretherton, 1980). However, clear planning in tool use only manifests itself in the second year of life, when better grasping patterns and flexible use of tools can be observed in infants (McCarty, Clifton, & Collard, 1999; Van Leeuwen, Smitsman, & Van Leeuwen, 1994). The rapid development of tool-related behaviors is observed after the age of two (Rat-Fischer, O'Regan & Fagard, 2012). In the third year, children can easily generalize tool use functions (Brown, 1990), and four-year-old children have already started to understand the intended design of tools and used tools (Defeyter & German, 2003). In all the studies mentioned above, children do not need to change the shape of the tool to solve a novel problem or use a familiar tool in a problem requiring multi-step actions to solve. However, when it comes to constructing complex patterns with objects, such as combining small sticks into a hierarchical novel shape, children have great difficulties until the age of five to six (see, Greenfield, 1991). Only a handful of studies attempt to explain why novel tool making and constructing complex patterns is hard for preschool children, or why they use familiar tools for multi-step problems. In this section, the focus is on two types of technical innovation: using familiar tools to solve multi-step novel problems, and tool innovation via fashioning or constructing a tool, or combining objects. However, first, one-step tool use behavior will be discussed and compared with non-human animals, including apes (henceforth, animal) given in the literature.

2.4.3.1. Innovative tool use

There are many types of innovative tool use behaviors among apes. Most of them require just one step to solve, but in the wild, innovative tool behaviors emerge and spread quite slowly. As pointed out in the previous sections, these innovations generally are innovated and reinnovated by individuals among apes. Their social learning ability is limited; thus, the spread of innovations among apes are mostly affected by environmental induction, stimulus enhancement or emulation learning (Ramsey, Bastian, & van Schaik, 2007; Reader & Laland, 2003;

Matsuzawa, 2001; Price, Lambeth, Schapiro, & Whiten, 2009). Reindl, Beck, Apperly and Tennie (2016), thus, argue that the innovative problem solving capacity of apes (mostly one step innovative tool use problems) might be similar to human children aged two to three. Reindl et al. (2016,) demonstrated that most of the two- to three-year-old children in their study could "spontaneously invent wild great apes tool-use behaviors". However, this age range is still large to distinguish two year olds from 3 year olds.

Most of these actions required only one step to solve the problem. However, if the task is a little more complicated (e.g., if it requires a multi-step causal structure), it is challenging for young children. Want and Harris (2001) showed that none of the two-year-old children could spontaneously solve the trap tube problem (see section 2.4.2.1), and out of 39 children in the three-year-old group, only five completed the task. However, two- to three-year-old children can be successful in familiar means-end problem solving with tools, even if two-steps are required to complete the task. In the study by Nagell, Olguin and Tomasello (1993), two-year-old children and chimpanzees were presented with a task in which they needed to change the position of a rake and fetch the reward (two-steps) or use the rake without changing the position (one-step). The performances of two-year-old human children and chimpanzees were comparable. Although most of the subjects were good at one-step problem solving, only one child and none of the chimpanzees could spontaneously solve the two-step problem. However, all the subjects were interested in using tools, as evident from the high frequency of tool use. For three-year-old children, both problems were easy to solve, but it should be noted that this task required finding a new behavioral techniques (see section 2.4.2.1), and children are familiar with such types of tool use behaviors. The real challenge is solving multi-step innovative problems in novel tasks.

2.4.3.2. Using familiar tools in novel ways: Floating peanut task and Aesop's fable

As shown in section 2.4.3.2, three-year-old children can solve two-step familiar tool problems via inventing behavioral techniques. In contrast, at this age, children have great difficulty in using familiar tools in cognitively demanding tasks, such as the *floating peanut task* (here onwards, *floating object task* for children) and Aesop's fable (see section 2.4.2.2.1, Figures 12 and 13) until the age of seven or eight. Hanus, Mendes, Tennie, and Call (2011) presented the floating object task with a pitcher filled with water. There were two conditions: wet and dry. In the wet condition, a quarter of the tube was filled with water, and in the dry condition, there was no water in the tube (see section 2.4.2.2.1 for the details of the apparatus). There were three age groups (four, six, and eight) and 24 children in each age group. The results revealed that only two children from the four-year-old group could solve the task spontaneously, and they were both allocated to the wet condition. Among six-year-olds, 10 were able to solve the task (four and six in dry and wet conditions, respectively). Fourteen children in the eight-year-old group could solve the task, and only five of them were in the dry condition. These results demonstrate that only a few four- to six-year old children can solve the floating object task. Furthermore, most of these innovators were in the wet condition of the task, which might show that children need the problem to be facilitated perceptually. These results were replicated several times in different conditions. In a study by Nielsen (2014) conducted with four-year-old children only in dry condition, only two children used water as tool in an attempt to get the toy out of the tube.

Further evidence of young children's inability in tool innovation with familiar tools comes from studies using Aesop's fable (see section 2.4.2.2.1 for further information about this task). Cheke, Loisse, and Clayton (2012) conducted a comprehensive study with different variants of the Aesop's fable task with four- to 10-year-old children. After training children with an apparatus that they could insert a ball inside a horizontal tube in order to get a reward, Cheke et al. (2012) presented the children with a series of tasks. In the first task, the children were presented with two tubes: one containing water and the other containing sawdust. Only 10% of the children added stones to the tube with water, but they did put stones into the tube with sawdust in at least three out of five consecutive trials. More surprisingly, only 5% of the children could solve all the five trials without an error. After these five trial, the children were only given the wet condition; however, the given objects were those that would either sink or float. Only 13 of 80 children added only sinking objects in three consecutive trials. The performance of the children in a more complicated Aesop's fable task was even poorer (see U-tube task, Cheke, Loisse, & Clayton, 2012). The researchers claim that the performance of children in the first two tasks were comparable with New Caledonian crows, rooks, and Eurasian Jays. However, in an incentively manipulated study, Miller et al. (2017) demonstrated that children might not need perceptual-motor feedback to solve Aesop's fable tasks. However, the results from the rooks and New Caledonian crows seem to suggest that they gained feedback after each stone was dropped into the tube, rather than anticipating all the action steps to solve the problem. In contrast, their problem solving was based on a one-action step followed by perceptual-motor feedback (see section 2.4.2.1 for further discussion on this topic). Children after the age of seven could actually anticipate future actions and plan the sequences of actions hierarchically. However, there is also some evidence that ravens, for example, can flexibly plan and demonstrate ape-like planning patterns and cognitive skills (Osvath, Kabadayi, & Jacobs, 2014; Kabadayı & Osvath, 2017; Kabadayi, Taylor, von Bayern, & Osvath, 2016; Osvath & Kabadayı, 2018).

These findings show that children are very immature in tool innovation with familiar objects or water before the age of eight, and five- to seven-year-old children's capacity in solving floating object and Aesop's fable tasks are close to the performance of crows. Further comparative research is needed in order to make sound conclusions in comparative studies (e.g., human children vs non-human apes vs crows).

2.4.3.3. Innovation via constructing or fashioning a tool: Tool making

In section 1.1., a basic definition of tool innovation was provided and different types of tool innovations have been described in previous sections. In this section, and the following chapters the focus will be on tool making in children.

Cutting et al. (2011) define tool making as two stages: *tool innovation* and *tool manufacture*. They define tool innovation as the first stage of tool-related behaviors in which the idea of a tool occurs in a non-social, spontaneous way. Tool manufacture is making a tool after social learning. On the other hand, cultural innovations may also appear during social interaction through the recombination of previous information and exploration in an iterative fashion (Spratt, 1989; Bargatzky, 1986; Barnett, 1953), as in cultural evolution (Carr, Kendal, & Flynn, 2016). The source of innovation may thus vary; while some innovations occur via independent inventions and chance factors, others may appear after observing modifications to the tool or during social interactive processes. In this thesis, the focus is not on long term cultural innovations; therefore, tool innovation is defined as a kind of individual; in other words, 'asocial' learning. For further information, see section 3.2.1.

The *hook task* introduced in sections 1.1 and 2.4.2.2 was adapted for use with children by Beck et al. (2011) and Cutting, Apperly and Beck (2011). In this task, children could use a pipe cleaner to make a hook shape and insert it inside a long transparent vertical tube to pull the bucket out in order to obtain the sticker inside the tube (see sections 3.2.3 and 3.3.2). Most children are unable to solve this task until the age of seven or eight.

So, what hampers young children from solving this problem? They are able to use familiar tools in their first year (Connolly & Dalgeish, 1989), flexibly adapting their grasping patterns in familiar tool use (McCarty, Clifton & Collard, 1999) and solving various means-end tasks in their second year (Brown; 1990; Bates, Carlson-Luden, Bretherton, 1980). Two- to three-year-olds can spontaneously invent novel behaviors requiring using a tool in one step (Reindl, Beck, Apperly & Tennie, 2016). Four- to six-year-old children's problem solving ability in tasks requiring multi step action is evident in the literature (Klahr & Robinson, 1981). It seems that all the pieces are available for four- to six-year-old children to solve the hook task, but they cannot do it.

In the hook task, if four- to five-year-old children are given both straight and bent (into a hook shape) pipe cleaners, most of them select the functional one, namely the bent pipe cleaner. Their difficulty in innovating tools in the hook task before the age of eight cannot be explained by not becoming familiar with the task materials before the experiment (Beck et al., 2011) or not understanding the task demands (Chappell, Cutting, Apperly, & Beck, 2013). Besides, these results are not task-specific (Cutting, Apperly, & Beck, 2011), tool-specific (see Chapter 4), or culture-specific (Nielsen, Tomaselli, Mushin, & Whiten, 2014; Frick, Clément, & Gruber, 2017). Prompting children to find alternative solutions (Chappel et al., 2013), explaining the task in alternative or interesting and real ways (Cutting et al., 2011; Neldner, Mushin, & Nielsen, 2017), and giving children time to explore the materials when the hook task has already been presented (Chappel et al., 2013) do not increase the success rate of tool innovation before the age of seven. Their difficulty in this task also cannot be explained by permission issue regardless of whether children were allowed to change the shape of the material. Changing the instructions or clearly demonstrating that the shapes of the tools are allowed to be changed does not increase innovation rate (Cutting et al., 2011). However, the results from studies are not all negative. Sheridan, Konopasky, Kirkwood, & Defeyter (2015) recruited three to seven-year-old children visiting a museum, which is an interesting place to seek participants for the study. The findings showed that there were more tool innovators in this population, and Heriden et al. (2015, p. 4) explained this outcome as "(i) the children's museums's making centre environment primes children to think of tool manipulation and innovation more readily; (ii) the environment, with its free access to use and take materials, reduces the inhibition children may have tend to bend or otherwise alter materials belonging to the experimenter." Recently, Neldner, Mushin, and Nielsen (2017) showed that three to five-year-old children were more successful in solving the hook tasks spontaneously if the affordance visibility of the pipe cleaner increased. Moreover, in order to make the task results comparable with the studies with crows, Whalley, Cutting and Beck (2017) conducted a study in which four- to seven-year-old children were given the opportunity to use a bent pipe cleaner to solve the hook task or were shown a bent pipe cleaner before being given a straight pipe cleaner to be used in the hook task. Whalley et al. (2017) clearly demonstrated that prior experience with the bent pipe cleaner greatly increased children's success. Children can also transfer their knowledge of the hook task to similar hook tasks (Beck et al., 2014). Children after the age of four can utilize social information in the hook task. Their success rates in making a functional tool increase after an adult demonstrates a ready-made tool (a bent pipe cleaner), and they observe a tool making action demonstration or are shown all the steps to solve the problem (Bek et al., 2011; Cutting et al., 2011; Nielsen et al., 2014). Section 3.2.2 presents further information on the relation between social learning and tool innovation.

Although some explanation has been given, the critical question concerning why young children of a certain age cannot make tools has not been answered. In the hook task, they are aware of the functional material; they can select it, or in some cases, they can explain the kind of tool that could be used to pull the bucket out, but they appear unable to make a similar tool (a hook) with the available pipe cleaner (see Chapter 3). Here, their problem does not appear to be related to the type of task. Young children do have difficulty in the loop task (see section 2.4.2.2.2 and Figure 14), as shown in the study conducted by Tennie, Call, and Tomasello (2009), in which none of the four-year-old children could spontaneously create a loop and pull the platform toward themselves to obtain the reward. In the following section, possible explanations are presented concerning the factors that could contribute to children's tool.

2.5. Developmental and cognitive science of tool making

2.5.1. Motivational factors

From an evolutionary viewpoint, innovativeness is highly related to motivation (Sol, 2016). Species that have a high level of innovations do not have aversion toward novel objects (neophilia); thus, they are not neophobic (Greenberg, 2003). However, these biological tendencies are at the species level, and animals have evolved mechanisms to regulate (or not) their emotional responses toward novel objects (Navarrete & Laland, 2016; Sol, 2016).

From an ontogenetic perspective, one of the factors impinging upon innovativeness might be the motivation to explore (Carr, Kendal & Flynn, 2016). Accordingly, Gibson and Pick (2003) indicate that infants do have high motivation to explore, especially in terms of haptic exploration, which mostly results in self-learning (see section 2.1.2). It has been stated that *curiosity* and *exploration* might underline childhood innovations a contributory factors (Carr, Kendal, & Flynn, 2016; Riede et al., 2017). However, whether individual differences at the level of curiosity, tendency for exploration and neophilia affect tool innovation should be carefully examined. Children who have a high level of motivation in different aspects (curiosity, exploration and neophilia) may obtain better results from innovation tasks.

2.5.2. Perceptual-motor factors: experience and familiarity

Gibson and Pick (2003) argue that action and perception are reciprocal processes (see section 2.1.2). During the developmental process, children not only learn about objects in their environment perceptually, they also learn the effects of the objects. This action and action-effect bidirectional relation has been highlighted in the ideo-motor approach (Stock & Stock, 2003; Paulus et al., 2011). Beginning from the first years, children represent perceptual elements with their possible action consequences. For instance, Bates et al. (1980) claim that children may anticipate the relation between tool and target. In this respect, experience with the task or tool may facilitate the motor capacities of children. As Keen (2011) indicates, western children have great amount of experience with a spoon, and beginning from the second half of the first year, children's motor control with spoon for eating is greatly facilitated. Thus, familiarity and experience might be important factors for tool innovation. In a recent study, Whalley, Cutting and Beck (2017) demonstrated that showing a bent pipe cleaner or allowing children to use the pipe cleaner to pull the bucket out in the hook task before the tool innovation test trial increased innovation success. These results direct attention to the affordance of the pipe cleaner. Neldner, Mushin, and Nielsen (2017) also used the hook task, but they increased the affordance visibility of the pipe cleaner. They presented a pipe cleaner with one end formed into a loop and the other end bent like a hook. Since the size of the looped pipe cleaner was not appropriate to pull the bucket out, the children needed to straighten the looped part and then use the bent side of the pipe cleaner to solve the task. Indeed, children who were given the looped pipe cleaner were more successful than the children receiving a straight pipe cleaner. Thus, these two studies demonstrate the immediate effect of using or seeing the hook shape. These manipulations might be related to facilitating the total number of processes required to solve the hook task. Based on the statistical and observational results of the first study conducted for the current research (see Chapter 3), it is argued that the children could imagine an ideal tool in the hook task. For instance, some children clearly stated that a bent cane would help to pull the bucket out (see section 3.5.4). Children can also think divergently about the pipe cleaner; in other words, they are quite flexible in finding alternative uses of the pipe cleaner (see Chapter 4). It is considered that their difficulty lies in the tool making action part of the problem steps. In order to test this claim, in Experiment 3, a group of children were given a soda straw. The bending action and the relation between the soda straw and a receptacle related to goal (bending the soda straw and getting the liquid) are within the action repertoire of children. Therefore, using a soda straw might actually trigger the child’s action repertoire and facilitate the use of the soda straw in an alternative way. This tool and action familiarity was seen to increase the children’s tool making performance. For further information about perceptual-motor factors in tool making, see Chapter 4.

2.5.3. Executive function and problem solving: from inhibition to insight

Making tools to solve some problems requires executing a number of steps to achieve the goal. Thus, sequencing actions to reach the goal necessitates a mechanism that can retain these steps in the memory, inhibiting prepotent responses and planning future actions. At this point, the role of working memory and executive function during tool making (including tool innovation) is critical

(Wynn, 1994; Coolidge & Wynn, 2005). Carruthers (2013, p. 1371) define working memory as a "domain-general subsystem of the mind that enables one to activate and sustain (sometimes via active rehearsal) a set of mental representations for further manipulation and processing". Alloway and Alloway (2013) point out that it is the working memory that provides to control over goal-oriented behavior, and it is closely related with consciousness. Executive function, on the other hand, is a part of the working memory system. Representational components that are held in working memory are further maintained and restructured by executive function (Baddeley, 2007). In the process of maintaining and restructuring the representations, one mechanism might be crucially important during the process of tool innovation and manufacturing, which is the capacity to inhibit prepotent responses (Coolidge, & Wynn, 2016). Inhibition may be also closely related to the manufacturing process of tool making. In the hook task, children should not only inhibit prepotent responses related to tool itself (e.g., using the tool as-is or insisting on the same action plan with the straight pipe cleaner), but they should also observe the experimenter in the second phase and restructure their action plan related to the newly acquires social information. Inhibition and social learning might be closely related (Bjorklund & Kipp, 2002).

Although we did not test the relation between spontaneous tool innovation and insightful problem solving in our studies (see Chapter 3-to-5), the role of insight in novel problem solving has been extensively emphasized in the literature (see Chapter 6). The possible role of insight in tool innovation require different experimental designs than the ones that have been given. So that, we suggest a new method to reveal the effect of insight into tool innovation in the last chapter.

2.5.4. Social cognition, dyadic interaction and cultural learning

In section 2.3, it was indicated that beyond their goal-directed use of tools, infants and children may be able to understand the goal-directed actions of others. This situation shows the level of social learning among babies. In the later years, children become proficient social learners. Beck et al. (2011) and Cutting et al. (2011) demonstrated that showing how to bend the pipe cleaner or a ready-made pipe cleaner facilitated tool making. Thus, it can be easily asserted that children are good at tool manufacturing but not in tool innovation. However, before their 5th year, children have difficulty in tool manufacturing either (Cutting et al., 2011; Gönül et al., 2018). Although the results regarding tool manufacturing are clear, what children socially may learn from tool making action or read-made tool demonstration begs for investigation. In the hook task, children may or may not connect the social information given by the adult experimenter regarding the solution of the task. For instance, after demonstrating the action patterns of hook making action, a child may only copy the shape of the demonstrated tool without realizing its relation to goal, in other words mimic the hand movements of the experimenter or just learn the affordance of the pipe cleaner. The child may or may not connect this information to the task elements. On the other side, children may truly understand the experimenter's aim of showing the action pattern and connec it to the goal. In this case, it might be imitation. In Chapter 3 and 4, one of our arguments is that independent of the type of social learning mechanism, if a child socially learn the adult's demonstration, they probably have better inhibition or hierarchical representational skills. Inhibition and hierarchical representation might be intrinsically interwoven with tool making ability as the literature suggests. So that, the crucial point may not be the type of social learning mechanism but whether children could inhibit their prepotent responses to overcome the problem, focus on the adult's actions, and/or connect social information to the task elements hierarchically.

Additionally, the crucial role of social learning is also emphasized by action-perception researchers. As Schütz-Bosbach and Prinz'in (2007) state, the two-way interaction between action-perception is important in developing and organizing a person's action-perception repertoire. In this two way interaction, observing another person's actions in a social context may provide *joint attention* and *perceptual common ground* that may create joint action (Sebanz et al., 2006), which may help to reorganize the cognition. Furthermore, not only observing another ones' actions, but also observing one's own actions may change the processes of cognition (Knoblich & Flach, 2003). Morever, pre-school and school-children not only learn from adults, but they also learn many –aspects of tool use and tool making from their peers. The *social diffusion* method (a method investigating the transfer of cultural techniques from one person to another one in chains, generally with children who are taught to use one tool or any unit and wanted to convey this knowledge to their peers) was used by Flynn and Whitten (2010) and Hopper et al. (2010) to reveal the social learning readiness of pre-schoolers from their peers. However, in the social diffusion experiments, in order to solve the task or use the tool or any other item, the experimenter should first show one child what is required. In this way, the element to be investigated is not how the children proceed with the task only with aid of their peers, but how the knowledge given by an adult to the first child at the beginning of the chain is transferred to the other children. More complex tool using patterns in chimpanzees and humans may be based on the complex social behaviors. This has also been shown by archeological evidence of hominids' living areas, because using and manipulating tools are mostly transformed socially with language, imitation, teaching and become parts of the culture (Boesch & Tomasello, 1998). At this point, the Cultural Intelligence Hypothesis asserted by Hermann et al. (2007) and Tomasello (2009) should be emphasized, since this hypothesis presents the idea that increasing social communication and shared information may enhance social and individual intelligence. Based on this claims, Chapter 5 of the thesis is dedicated to unravel the social and cultural underpinnings of tool making and gives more information on the possible relation between social cognition and tool making in children.

2.5.5. From hierarchical structuring to recursive thinking and creativity

As emphasized throughout the previous sections, the literature shows that age and perceptual-motor properties (e.g., affordance relations and perceptual similarities) has a significant positive role on tool-related-behaviors. Beyond this, both representational factors (e.g., hierarchical structuring, insight, and planning) and social factors are significant contributors to the process of tool-related behaviors. Developmental studies show that human infants and children start to use tools from early months onwards and use tools for different problem solving situations especially after two years of age (Rat-Fischer, O'Regan & Fagard, 2012). Greenfield (1991) claims that this spurt in tool use is related to better hierarchically sequential structuring abilities in children. According to Greenfield and Schneider (1977), children's increase in complex hierarchical representations, especially after the age-of-five, can be explained by construing better part-whole relations. Mounoud (1996) points out that such part-whole representations are recursive. The capacity of recursion can be also seen in pretend play or imaginative and divergent thought where an object is used beyond its perceptual and contextual boundaries; in other words, in symbolic thought (Callahan, 2013).

Hoffecker (2007) sees the capacity for innovation as a recursive process. There are two crucial steps in recursive thinking: (1) constructing sequential information in a hierarchical fashion to construe embedded relations and (2) generating an infinite array of combinations based on the hierarchical structuring of information as in creative and divergent thinking. The capacity for recursion in tool-innovation may manifest itself in representing and reasoning about the physical world, in terms of causal understanding, hierarchical representation, and divergent thinking and social cognition; i.e., social learning or joint action, as well as in their interaction.

Innovation is a complex process as Spratt (1989) defines, and the recursive process of tool-innovation might be affected by developmental, perceptual-motor, representational and social processes. However, the effect of these factors must be clearly shown.

2.6. The aim of this thesis

As indicated in Chapter 1, this thesis aimed to reveal the triggering/facilitating factors of children's tool making ability. Beck et al.'s (2011) 'bending task' paradigm (*hook task*) was used, in which children need to make a hook in order to reach a sticker in a small container inside a bottle. The hypothesis was that to innovate a functional tool, the sequence of information about a tool and task needs to be ordered hierarchically (see Greenfield, 1991), and to focus on the goal and social information, redundant or conventional responses should be inhibited (response inhibition) (see Bjorklund & Kipp, 2002). Also, alternative uses of the tool (divergent thinking) should be evaluated (see Carr, Kendal & Flynn, 2016). However, this process may be affected by several factors, such as developmental (age; Beck et al., 2011), perceptual-motor (familiarity and salience of affordance of the tool), and social (social learning, dyadic interaction, cultural norms). This task does not require a joint action; however, a joint action may increase the decision-making processes about a task (Tomasello et al., 2005). Furthermore, different types of innovations are influenced by cultural dynamics (Muthukrishna & Henrich, 2016).

Study 1

In Experiment 1, we investigated the role of representational factors [predictor tasks: response inhibition (day-night-stroop task) and hierarchical structuring (hierarchical-tree-structuring task)], and social learning with 52 Turkish preschoolers aged three to six years. The children were required to undertake the tool innovation task with a pipe cleaner and a piece of string. This task was presented in the following three phases: Phase 1 was implemented without prior demonstration, and Phases 2 and 3 repeated the researcher's demonstration of tool making. The children were given the predictor task after the hook task. In the day-night-stroop task, children were asked to say ‘day’ when shown a black card with bright stars and the moon, and to say ‘night’ to the white card with a shining sun. In the hierarchical-tree-structuring task, children were given ten short sticks to create a copy of a simple tree-like shape that they were shown.

Study 2

In Experiment 2, 20 Turkish adults were asked to solve the hook task with one of the three tools (pipe cleaner, bendable straw, and small and long sticks that could be combined to make a hook), and their familiarity and saliency of affordance were evaluated. In Experiment 3, 75 Turkish children aged five to seven years were given a pipe cleaner, straw or sticks (three groups). The children were scored from 1 to 4 according to their success in one of the following four phases: (1) without prior demonstration, (2) after demonstration of a ready-made tool, (3) after demonstration of tool-making, and (4) totally unsuccessful. Subsequently, the children were given the predictor tasks listed above and the divergent thinking task, in which they were prompted to consider alternative uses of two tools.

Study 3

In Experiment 4, the tool making results of the Turkish individual group from Experiment 3 (wooden sticks group) were compared with a dyadic 14 Turkish children of the same age. In Experiment 5, we compared the Turkish dyadic group with the New Zealand Dyadic group.

CHAPTER 3

STUDY 1: THE COGNITIVE ONTOGENY OF TOOL MAKING: THE ROLE OF INHIBITION AND HIERARCHICAL STRUCTURING[2]

3.1. Abstract

During last decade, the ontogeny of tool making has received growing attention in the literature on tool-related behaviors. However, the cognitive demands underlying tool making are still not clearly understood. In this cross-sectional study of (N = 52) Turkish preschoolers from 3 to 6 years of age, the role of executive function (response inhibition), ability to form hierarchical representations (hierarchical structuring), and social learning were investigated with the *hook task* previously used with children and animals. In this task, children needed to bend a pipe cleaner to fetch a small bucket with a sticker out of a tall jar. This study replicated earlier findings that preschool children have great difficulty in tool innovation. However, social learning facilitates tool making especially after 5 years of age. Capacities to form hierarchical representations and to inhibit prepotent responses were significant positive predictors of tool making after social learning.

Keywords: Tool innovation, tool making, tool manipulation, response inhibition, hierarchical representation, ontogeny.

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3.2. Introduction

Making and using tools expertly is considered one of the most distinctive abilities of humans (e.g., Oakley, 1957; Vaesen, 2012) and an area in which humans have become specialized (see Defeyter & German, 2003). However, researchers working on comparative behavioral and brain sciences emphasize that many other animals can use tools as well (Meulman, Seed, & Mann, 2013). Nevertheless, human material culture is far richer and human tool-making ability is more flexible as compared with our closest relatives. At this point, understanding the cognitive ontogeny of tool making would help us to better understand what renders our tool-making ability more flexible than that of other animals. In this study, we focused on two cognitive factors that have been highlighted in the literature on the phylogeny and ontogeny of tool-related behaviors: response inhibition (Bjorklund & Harnishfeger, 1995; Bjorklund & Kipp, 2002; Coolidge & Wynn, 2016) and hierarchical structuring (Greenfield, 1991). We claim that tool making requires inhibiting prepotent responses (response inhibition) and connecting information in a hierarchical fashion (hierarchical structuring) and tested this claim in Turkish 3- to 6-year-old preschool children.

3.2.1. From tool use to tool making

Studies show that making more precise plans with tools improves from 9 months to 3 years of age (Bates, Carlson-Luden, & Bretherton, 1980; Brown, 1990; McCarty, Clifton, & Collard, 1999). More recent studies indicate that 20-month-old infants can anticipate the future outcomes of tool use actions (Paulus, Hunnius, & Bekkering, 2011) and that 2-year-old children can use unfamiliar tools in novel problem-solving tasks (Barrett, Davis, & Needham, 2007). Beyond that, 2- to 3.5-year-old children can devise some tool use solutions—which are also observed in apes—without social learning. This observation seems to suggest that great apes' and young children's physical cognition might be similar in this respect (Reindl, Beck, Apperly, & Tennie, 2016). Although using tools for solving simple problems is relatively easy for preschool children, creating novel tools spontaneously—in other words, tool innovation—is challenging for preschoolers (Beck, Apperly, Chappell, Guthrie, & Cutting, 2011).

Cutting, Apperly, and Beck (2011) distinguished two types of tool making: ''tool manufacture (the ability to make tools after instruction or observation) and tool innovation (independently making a novel tool to solve a problem)" (p. 497; see also Chappell, Cutting, Apperly, & Beck, 2013). According to Ramsey, Bastian, and van Schaik (2007), ''innovation is the process that generates in an individual a novel learned behavior that is not simply a consequence of social learning or environmental induction" (p. 395). Tool innovation is a kind of behavioral innovation in the physical realm (Carr, Kendal, & Flynn, 2016) that requires a new method of tool construction or new ways of using familiar tools for novel problems (Nielsen, Tomaselli, Mushin, & Whiten, 2014). Please see section 2.4 for further information about innovation, its evolution and development.

Beck et al. (2011) demonstrated that until 7 years of age, children have great difficulty in tool innovation in what the authors called the bending task (from here onward, the *hook task*) in which children need to bend a pipe cleaner in the form of a hook to retrieve a small bucket inside a transparent vertical tube. However, these children are good at tool manufacture, in other words, tool making by way of social learning mechanisms, specifically tool-making action observation (Cutting et al., 2011). Further studies indicate that their difficulty in tool innovation cannot be explained by the type of the task (Cutting et al., 2011) or by practicing with the tool or not prior to the experiment (Cutting, Apperly, Chappell, & Beck, 2014). Given that preschool children are good at using tools and understanding the function of tools, their great difficulty in tool innovation is unexpected. This might be explained by their inability to produce actions according to their mental simulations and imaginations. For example, Cutting (2013) observed a case where a 3-year-old child gestured a hook shape for the solution of the hook task but did not made a hook shape with the pipe cleaner. This ability to produce actions according to mental simulations spontaneously might improve with age. Considering the rarity of tool innovation before 7 years of age, we focused on social aspects of tool making and its cognitive bases in this study.

3.2.2. Tool-related behaviors and social learning

Social learning and innovations might be the leading engines of our material culture (Carr et al., 2016; Legare & Nielsen, 2015; Lotem, Halpern, Edelman, & Kolodny, 2017). There might be an evolutionary link between brain size and frequency of social learning and innovations (Reader & Laland, 2002). In the hook task, different types of social information might be provided regarding different steps of the tool-making process. Ontogenetic studies with the hook task indicate that different types of social information facilitate tool-making performance in preschool children in different degrees, demonstrating (a) a ready-made hook (end-state tool demonstration; Chappell et al., 2013), (b) how to bend the material into a hook shape (tool-making action demonstration; Beck et al., 2011), (c) the tool-making action and inserting the tool into the tube without raising the bucket (Neldner, Mushin, & Nielsen, 2017), or (d) all the action steps from hook making to fetching the bucket (Nielsen et al., 2014). Some studies indicate that some 4-year-old preschoolers still might not be able to make a tool to solve a task even after demonstration of the tool-making action or the ready-made functional tool by an adult (Beck et al., 2011; Cutting et al., 2014). Despite these restrictions, young children still use social information better than chimpanzees to solve tool-making problems (see Tennie, Call, & Tomasello, 2009).

These results indicate that social learning (and cumulative cultural learning) might be the main driver of our cumulative material culture (see Buttelmann, Carpenter, Call, & Tomasello, 2008; Price, Caldwell, &Whiten, 2010) rather than individual innovations. Our social learning capacity and cultural know-how might have been crucial for humans' survival under different environmental conditions and might have induced progress in making ever more complicated tools (Henrich, 2016). Although it is known that social learning facilitates tool making, the cognitive underpinnings of socially facilitated tool making are still not well understood.

3.2.3. Possible cognitive mechanisms for tool making: response inhibition and hierarchical structuring

According to Nielsen et al. (2014), ‘‘knowing how to make a hook from a pipe cleaner is not enough'' (p. 392) for succeeding in the hook task. Rather, integrating tool, task, and goal information is required for solving the problem. In this respect, tool making might require two cognitive skills for the integration of the task components: response inhibition and hierarchical structuring.

Response inhibition can be defined as ‘‘the ability to suppress habitual plans and substitute alternate actions in line with changing problem-solving demands'' (Knudsen et al., 2015; p.214). Manrique, Völter, and Call (2013) and Knudsen et al. (2015) claimed that inhibition of prepotent responses and preexisting plans might be crucial for innovations, as observed in great apes (see section 2.4.2.2.1

and 2.5.3). Beyond generating novel behaviors as in tool innovation, inhibition of responses might have also helped humans to attend to and use social information and control instinctive responses during evolution (see Bjorklund & Kipp, 2002; Coolidge & Wynn, 2016). In line with this perspective, inhibition of prepotent responses might help children to focus on what the experimenter demonstrates in the hook task and prevent activating their own (inefficient) action plan. Thus, during tool making, children may connect information from the social environment to the instrumental requirements of the task and succeed in making functional tools to achieve their goal (see Bjorklund & Kipp, 2002; Legare & Nielsen, 2015). More precisely, children might first need to inhibit their prepotent responses both related to the tool, such as the tendency to use the pipe cleaner in a straight form (if given in this format) as shown by Cutting et al. (2011), and related to their previous actions to achieve the goal according to their action plan. Thus, they need to make the connection between task requirements and tool knowledge while inhibiting their responses and to focus on new solutions demonstrated by the experimenter. Even though Beck, Williams, Cutting, Apperly, and Chappell (2016) did not find a significant relation between spontaneous tool innovation and executive functions, the role of executive functions during the process of tool making has been underlined (see Wynn, 2002). Inhibition, one of the components of executive function, has a critical role in both evolution and development (see Bjorklund & Kipp, 2002; Herrmann, Call, Hernández-Lloreda, Hare, & Tomasello, 2007). The enhanced capacity to inhibit responses or representations might be just as important as knowledge acquisition or even more so (Deacon, 1997; Diamond, 1990). Some researchers consider the ability to inhibit responses as the most distinctive feature of the human prefrontal cortex (Passler, Isaac, & Hynd, 1985). Beck et al. (2011) showed that children tended to use tools as they are even if they might need to change the shape of the tools; therefore, children might not be inhibiting their tendency to use the tool as it is. Besides response inhibition, there might be another factor underlying children's tool-making ability, namely construing a hierarchical relation between elements such as the tool and task properties and social information (if available).

Langer (1998) proposed that children's ability to make three-level classifications demonstrates their ability to make tree-like hierarchically embedded representations of classes. Greenfield (1991) referred to this ability to make hierarchical representations as hierarchically organized sequential behavior, which can be observed in tool use or object construction. Greenfield and Schneider (1977) showed that after 5 or 6 years of age, children were better than younger children at constructing hierarchical shapes with short sticks. The complexity of the sequential construction process increased dramatically with age. This ability to execute actions based on newly acquired rules requires structuring the knowledge hierarchically and can be seen in many types of executive function tasks, including various types of inhibition tasks (Zelazo, 2004) and theory-of-mind tasks (Perner, Stummer, & Lang, 1999). Grossman (1980) and Fitch (2014) proposed a central processor building hierarchical representations of embedded materials or stimuli. This central processor in hierarchical planning might not function well in patients with neurological disorders (see Greenfield, 1991; Grossman, 1980) or in children with language-based learning disabilities because language also requires hierarchical structuring (Kamhi, Ward, & Mills, 1995). Beyond hierarchical object construction, the ability to construct hierarchical representations also might be required for social learning (Byrne & Russon, 1998). For instance, preschool children can handle complex tool use tasks if the action patterns for the possible solutions are demonstrated hierarchically (Flynn & Whiten, 2008a; Whiten, Flynn, Brown, & Lee, 2006) so that, in the hook task, children with better hierarchical structuring capacities might be able to connect the task elements and the goal (see Figure 16). For further information about the relation between hierarchical structuring and tool making, see section 2.2.3.

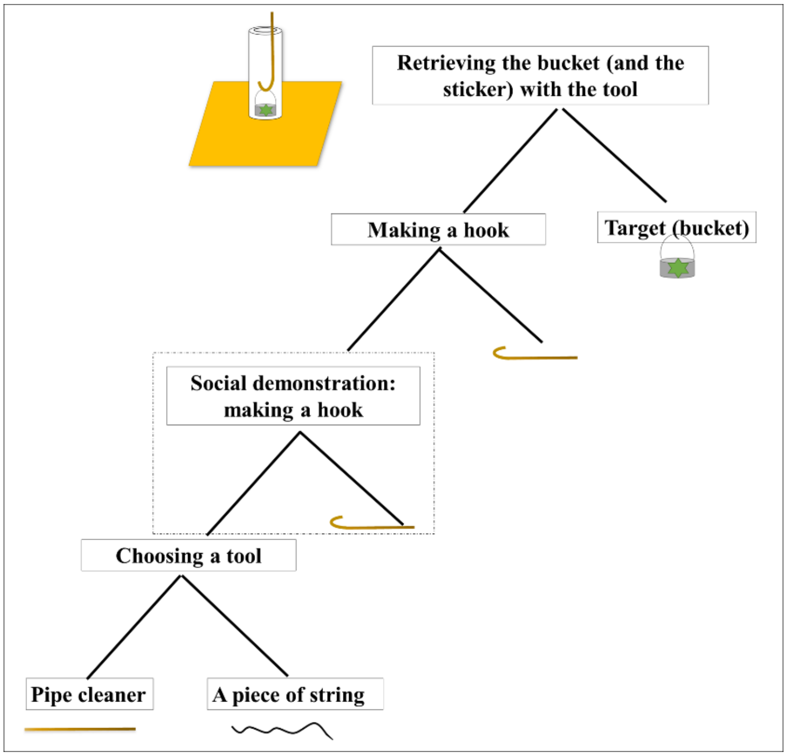

Figure 16: Schematic tree representation of the hook task. Straight lines show the relation between task elements and the goal (retrieving the bucket). The rectangle with the dashed line represents optional insertion of social demonstration of tool making.

In this study, the same hook task (see Figure 17) applied by Cutting et al. (2011) was used but with a slightly different procedure (in the third phase; see Method). Considering the developing social and executive function abilities, we focused on two age groups: 3- and 4-year-old and 5- and 6-yearold children. Beyond age and social learning, we made two predictions regarding the outcomes of the study related to inhibition and hierarchical structuring. The first prediction was that children with better inhibition abilities would come up with novel solutions or pay attention to the behavior of the experimenter. The ability to generate better and more efficient hierarchical representations is the basis of the second prediction, related to macro planning abilities (Grossman, 1980). We predicted that the capacity to construct hierarchical shapes is related to construing the hierarchical relations among the tool, task, and goal during tool making (see Figure 16).

Figure 17: Materials used in the hook task.

3.3. Experiment 1: Method

3.3.1. Participants

A total of 52 children participated in the study[3]: 30 3- and 4-year-olds (*M* = 50 months 3 weeks, *range* = 38–59 months; 18 girls) and 22 5- and 6-year-olds (*M* = 67

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[3] The sample size of the age groups was decided according to similar studies undertaken with similar age groups (Beck et al., 2011; Nielsen et al., 2014). Then, the *Statistical Power Analysis for the Behavioral Sciences* (Cohen, 1980) for the *Chi-Square* test was used to determine sample size according to 95% of power, 1 degrees of freedom and a 0.05 significance level. According to the power analysis, a sample size of at least 52 is recommended with high effect size. This sample size

months 3 weeks, *range* = 60–74 months; 10 girls). The reason why there were more children in the first group is that new participants needed to be tested due to missing cases in the predictor tasks (see ''Coding, data analysis, and data reduction'' section -3.3.4- below). All the participants were preschool children from four nursery schools in Ankara and Muğla in Turkey. They all were native speakers of Turkish, mainly from middle-class families and of the same ethnic composition. One additional child who could solve the hook task with a nonfunctional solution was excluded.

3.3.2. Materials

3.3.2.1. Hook task

The materials used in the warm-up stage and in the hook task were a pipe cleaner (length = 29 cm), a piece of string (length = 29 cm), a transparent plastic tube (height = 22 cm, width of opening = 4 cm) affixed vertically to a square wooden board (length = 30 cm), a small bucket (depth = 1 cm, diameter = 3.2 cm, length of handle = 9.5 cm), and some stickers that fit into the bucket (Figure 17).

3.3.2.2. Day–night and hierarchical tree structure tasks

For the inhibition task, the day–night task was administered using tokens of a ''white'' card and a ''black'' card. On the white card, a radiant sun was depicted. On the black card, a white moon and some stars were depicted. There were 18 cards (size = 13.5 - 10 cm). This task is used to measure inhibitory control as part of executive function in young children (Gerstadt, Hong, & Diamond, 1994; Simpson & Riggs, 2005). The hierarchical tree structure task was a simplified version of the task originally used by Greenfield and Schneider (1977). The materials in this task were 10 pieces of short wooden sticks (length = 4 cm, similar

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is similar to other studies investigating the cognitive underpinnings of tool making developmentally (see Beck et al., 2016).

to matchsticks) and an A4 size photo of the end-state tree shape made by the sticks (see Figure 18).

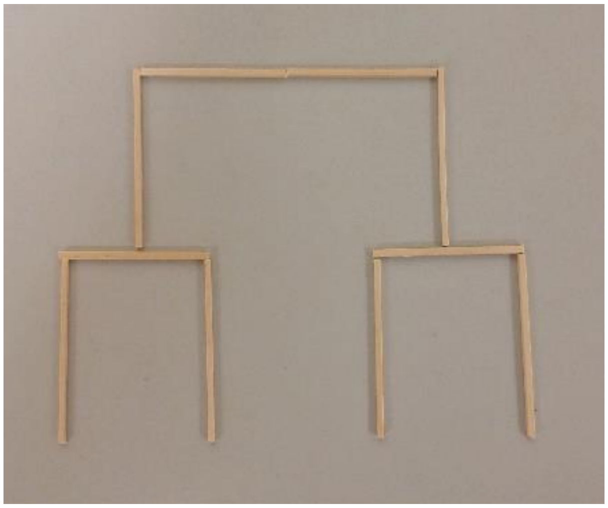

Figure 18: End-state photo of the hierarchical tree structure task.

3.3.3. Procedure

All participants were tested in a quiet room in their kindergarten by one of the experimenters (G.G. or E.K.T.). The materials used for the experiment were presented on a table, at which the child sat across from the experimenter. After the warm-up stage, the hook task was presented in three phases as described below. After this task, the day–night task and the hierarchical tree structure task were administered in a counterbalanced order.

3.3.3.1. Hook task

In this task, children needed to make a hook with the pipe cleaner and raise the bucket in order to get the sticker. After the warm up, this task was presented in three phases.

3.3.3.1.1. WARM UP

In the warm-up (see Cutting et al., 2011, 2014), the participants were presented with a piece of string, a pipe cleaner, and a short tube. This warm-up stage was very similar to the practice phase of Cutting et al. (2011). Both the experimenter and the participants used exactly the same materials throughout the warm-up. First, the participants were asked to roll the pipe cleaner around the tube. The experimenter and the participants rolled the pipe cleaner around the tube at the same time. Then, the experimenter removed the pipe cleaner from around the tube, asking the participants to do the same. In this way, the children could see that the pipe cleaner maintained its shape. Then, the participants were asked whether the pipe cleaner would return to its earlier shape if it were straightened. After this, the experimenter straightened the pipe cleaner. From this demonstration, it was expected that the participants understood that the shape of the pipe cleaner could be changed. Then, the experimenter made an ‘‘S” shape with the piece of string and asked the participants to do the same. By doing so, it was expected that children could compare a rigid tool with a nonrigid tool. The warm-up took about 2 min, and afterward the experimenter collected all the materials and placed them out of sight.

3.3.3.1.2. PHASES

After the warm-up, the participants performed the hook task as follows: spontaneous tool innovation (Phase 1), first tool-making action demonstration (Phase 2), and second tool-making action demonstration (Phase 3). In Phase 1, the experimenter said, ‘‘Do you see the sticker inside? If you can get it, you can keep it.” After that, the participants were presented with the tools (a pipe cleaner and a piece of string) and told, ‘‘You can use these ones.” The participants had 1 min to obtain the sticker. If the participants could not solve the task in Phase 1, the experimenter said, ‘‘Could you please put that tool down?” Afterward, the experimenter said, ‘‘Look at this.” The manipulation of the material (how to make a hook from the pipe cleaner) was demonstrated by the experimenter in a horizontal angle (Phase 2), and the experimenter said, ‘‘Now try it again.” The participants were given 30 s. If they were unable to complete the task in Phase 2, that phase was repeated (Phase 3). The third phase was added to investigate a possible persistence in using the same tools or performing the same actions.

3.3.3.2. Predictor tasks

After the hook task, the participants performed slightly modified versions of the day–night task and the hierarchical tree structure task in a counterbalanced order. For the day–night task (Gerstadt et al., 1994; Simpson & Riggs, 2005), the experimenter first showed the black card with a moon and stars on a black background and explained to the participants, ‘‘When you see this card, I want you to say ‘day’.” The experimenter told them to repeat what to say when they saw that card. When the participants repeated ‘‘day,” they were praised. The only modification was that the experimenter repeated the rule for the card again to ensure that the rule was clear to the participants. Then, the white card with a sun on a white background was presented and the rule was explained: ‘‘When you see this card, I want you to say ‘night’.” Again, the participants were asked to repeat ‘night’ when they saw that card and were praised after their correct repetition. Then, the rule for the card was repeated by the experimenter. This was the pretest part of the task. After the pretest, the white card was presented and the experimenter waited for a response from the participants and praised them if they responded correctly. Then, the black card was presented, and again the experimenter waited for the response from the participants and praised them if they responded correctly. These cards were counted as the first and second test trials if the responses were correct, but if any of the responses were not correct, the experimenter reminded the participants of the rules. The experimenter did not give any feedback to the children during the administration of the test cards. The order of the 16 trials was pseudorandom, and all the children were presented with the task in the same order: WBWBWBBWWBWBBWBW (where W= white card with the sun and B = black card with the moon and stars). Children could get scores from 0 to 16.

For the hierarchical tree structure task, first, the sticks were given to the participants. The photo of the target shape was placed on the table at a comfortable viewing angle, and the participants were asked to replicate the shape on the surface of the table using the sticks. Then, the photo was placed on the table. When the children told (or gestured to) the experimenter that they had finished, the experimenter retrieved the sticks and the photo.

3.3.4. Coding, data analysis, and data reduction

All tasks were video-recorded for later coding. For the hook task, to determine children's capacity for understanding the requirements of the task, their first contact (first touch) and first use of one of the tools (first use of the piece of string or the pipe cleaner) were coded. Tool-making success was coded for each phase. The success criterion was making a hook shape with the pipe cleaner and raising the bucket, in contrast to Cutting et al.'s (2011) success criterion, which was getting the bucket out of the jar. We believe that our measure is fairer, especially for the 3-year-olds. In some instances, very young children were clearly making a functional hook in Phase 2 and raising the bucket, but the bucket was inadvertently dropped at the opening of the jar because a pipe cleaner is a somewhat delicate tool.

If children manipulated the pipe cleaner (in any shape) but still could not use this tool for raising the bucket, it was coded as tool manipulation. The relation between tool-making success in phases and age groups was assessed with chi-square tests or Fisher's exact tests (FETs). This coding was done by one experimenter (G.G.) because the first touch, first use, tool manipulation actions, and tool-making success were very clear.

The data show that most of the children could make a functional tool after the first social demonstration of the tool-making action. To assess this breakpoint of social learning in tool making and its relation with other task measures (see below), the results of the tool-making success were converted into a linear (but dichotomous) variable according to the children's success in the second phase. The children could gain a score of 2 (successful in Phase 2; high tool-making score) or a score of 1 (successful in Phase 3 or unsuccessful; low tool-making score). To assess the participants' competence in building hierarchical representations, the following three measures were coded from the hierarchical tree structure task: hierarchical resemblance, hierarchical complexity, and tree structuring processing time (see online Appendix A Supplementary Material 1 for more information). Tree task error was also coded. Hierarchical resemblance is the measure of goodness of the copy of the model. If the children could copy the model exactly, they scored 10 out of 10 (sticks). The hierarchical complexity measure was based on graph theory as explained by Greenfield and Schneider (1977) with a slight difference (see Appendix A Supplementary Material 1). A score of 1 (1^2) was given for simple edges, 4 (2^2) for junctions of two edges, 9 (3^2) for junctions of three edges, and 27 (3^3) for junctions in the middle nodes (see Figure 19). The hierarchical complexity measure was calculated by summing the complexity numbers of the nodes. For example, the complexity of the shape shown on the left side of Figure 19 is 86. The range of this measure could be from 20 to 86 if all the sticks were used. Both the complexity and similarity measures were calculated by the two experimenters separately, and the incompatibilities (only three) were resolved by discussing them one by one. The last measure was tree processing time, which indicates the total amount of time in seconds from the moment the participants first touched a stick to the moment they finished constructing the shape. This measure was evaluated as the quantitative aspect of the ability to make and carry out hierarchical plans. This measure was coded by only one experimenter (G.G.) because the finishing time could simply be read off. Hierarchical structures made by the children varied to a great extent. See Appendix A Supplementary Material 2 for some examples of unsuccessful hierarchical structures made by the children.

The hierarchical structuring task results of 4 children in the 3- and 4-year-old age group were excluded from the main models and coded as tree task error; they did not want to finish the task (2 participants) or they became very nervous (2 participants). These children either said directly that they did not want to play the game or were distressed and played with only one or two of the sticks. The experimenter terminated the task for these children. The relation between tree task error and tool-making scores was analyzed later. In addition, data from the hierarchical structuring task of 1 child were excluded due to experimenter error.

To assess the participants' ability to inhibit responses, the following two measures from the day–night task were coded: inhibition latency and task error. Total inhibition latency was the total amount of time in milliseconds from the moment the card touched the table to when the participants articulated the first syllable of the correct responses (''ge-'' for ''gece,'' which means ''night,'' and ''gü-'' for ''gündüz,'' which means ''day'' in Turkish). Interrater reliability for 20% of the participants' reaction times (excluding the ones who made task errors) for all 16 trials (6 participants; 96 cases, including incorrect responses) was calculated by the two experimenters (G.G. and E.K.T.) separately. Cronbach's α was .94. Only correct responses were considered because they provide a more sensitive measure for response times in this task (Simpson & Riggs, 2005). Then, total inhibition latency was divided by the number of correct responses to obtain the inhibition latency. Responses lower than 200 ms and higher than 8000 ms were excluded. Participants who used a strategy for at least 14 of the 16 trials (7 children, all in the 3- and 4-year-old age group) in the day–night task were excluded from the main model, but their data were coded as task error (see Gerstadt et al., 1994). Its relation with the tool-making scores was analyzed later. These children were either saying ‘‘day’’ and ‘‘night’’ interchangeably and repetitively before seeing the cards (alternate error) or insistently saying ‘‘day’’ to the white card with the sun and ‘‘night’’ to the black card with the moon and stars (matching error). For detailed explanations of these errors, see Gerstadt et al. (1994, pp. 144–145) and Simpson and Riggs (2005). Day–night task data of 1 child were excluded because of experimenter error.

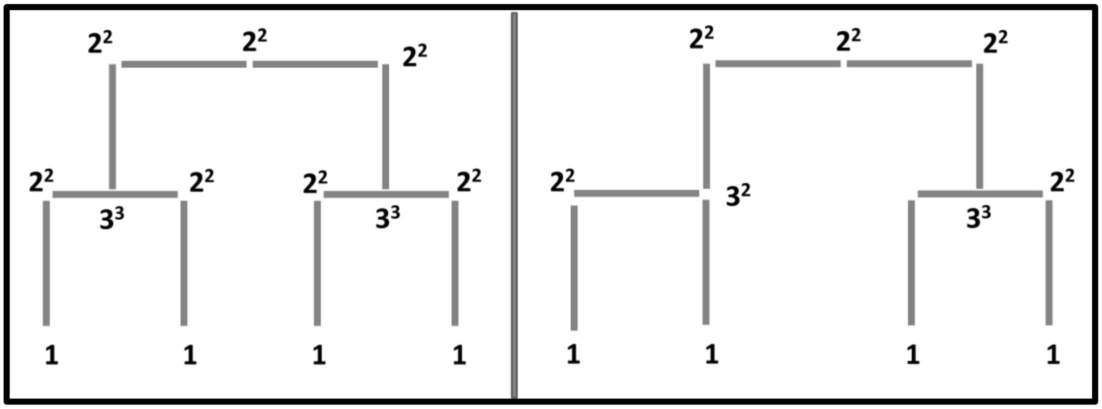

Figure 19: Two examples of the hierarchical complexity measure.

Because the data distribution of the dependent variable (tool-making scores) was non-normal, we calculated binary logistic regression with a generalized linear model (GLM) to predict tool-making scores with complementary log–log link function given that there were not many children whose tool-making scores were 1 (low score). Stroup (2013) stated that the GLM is a very powerful method to identify effects of the model in a non-normally distributed dependent variable, and he clarified that ‘‘the complementary log–log does not require symmetry and is thus, in theory, better able to fit binomial models for events that either occur very infrequently or occur almost—but not quite—all the time’’ (p. 317). In order not to increase Type II error, because of missing cases in either of the predictor tasks (13 missing cases in total: 5 for the hierarchical structuring task and 8 for inhibition latency), we did not use inhibition latency and hierarchical structuring task measures in the same model. Note that all GLMs make listwise deletion. A further model with a standardized hierarchical complexity measure was computed for clarification (see Results). Exploratory tests before the main GLMs (see Appendix A Supplementary Material 4) or follow-up tests after the models were provided; nonparametric or parametric tests were calculated according to normality of the distribution and/or homogeneity of variance of the dependent variables, and effect sizes were calculated as appropriate for the target test.

3.4. Experiment 1: Results

There were no significant differences between boys and girls on any of the scores ($p > .05$). Therefore, gender was excluded from the subsequent analysis. Binomial tests revealed that 5-to-6-year-old children were significantly more likely than chance to touch the pipe cleaner first than the piece of string ($p = .001$), but not 3-to-4-year-old children ($p = .585$); however, both age groups used the pipe cleaner significantly more than the piece of string ($p = .004$ and $p = .005$, respectively).

3.4.1. Tool Manipulation, Tool Making Success and Age

Only 11.5% of the children spontaneously manipulated the pipe cleaner in Phase 1, but not in a proper way. These children could not raise the bucket with their manipulated tool, as their pipe cleaners were either bent at the middle of the tool or the 'hook' shape was too big to raise the bucket. All the tool manipulators ($n = 6$) were successful in the second phase, and they were all in 3-to-4-year-old age group.

Most of the children could successfully make a tool after the first tool making demonstration (Phase 2), and 81% of the children could successfully made a tool in one of the three experimental phases (see Table 1). The descriptive results showed that 75% of the children were successful in Phase 2; however, only one child (2%) was successful in Phase 1 (tool innovation). Most of the children who were unable to succeed in Phase 2 were also unsuccessful in Phase 3 (see Table 1).

In Phase 2, after the first tool making demonstration, 60% of the 3-to-4-year-old children and all of the 5-to-6-year-old children were able to successfully retrieve the bucket, and the difference in Phase 2 success between age groups was significant, *FET, p* = .001, φ = .46. (If the participant was successful in any previous phase, the data were excluded from the subsequent analyses). Only two children (3.6%) managed to solve the problem after the second tool making demonstration (Phase 3), both from the 3-to-4-year-old age group (see Table 1). There were significantly more unsuccessful children in the 3-to-4-year-old age group than in the 5-to-6-year-old group, *FET, p* = .003, φ =.41.

Table 1: Success of Tool Making in Phases between Age Groups. Cells Represent the Total Number of Successful Children According to Age Groups and Phases.

		Success in phases			
		Successful			Unsuccessful
Groups	*N*	Phase 1	Phase 2	Phase 3	
3- and -4-year-olds	30	0	18	2	10
5- and -6-year-olds	22	1	21	0	0

3.4.2. Predicting Tool Making: Age, Tool Manipulation, Response Inhibition, and Hierarchical Representation

As the data show, most of the children were successful in the second phase. To unravel the very moment of social learning for the solution of the task (Phase 2) we gave scores according to children's success in the various phases, i.e., a score of 1 (unsuccessful or successful in Phase 3) and 2 (successful in Phase 2). The tool innovator (only 1, see Table 1) was excluded from all the subsequent analysis. Note that all children in the 5-to-6-year-old age group got the higher score (score 2). Please see Appendix A Supplementary Material 3 for the exploratory tests used for the preparation of the main GLM models and descriptive statistics of the covariate predictors (Appendix A Supplementary Material 3 Table 7).

Based on the exploratory test results and the aims of the study, a binomial regression with complementary-log-log link function was calculated using GLM to predict tool making scores. As explained in the 'Coding, Data Analysis and

Data Reduction' section, we did not include hierarchical structuring task measures and inhibition measure in the same model. Age group and tool manipulation were added as factors.

In the first model (Model 1, *n* = 46), test of model effect results indicated that the factors age group, *Wald* $\chi^2(1) = 49.216$, $p \leq .0001$, and tool manipulation, *Wald* $\chi^2(1) = 58.678$, $p \leq .0001$, and the covariate hierarchical complexity, *Wald* $\chi^2(1) = 5.31$, $p = .021$, were significantly related to tool making scores; but hierarchical resemblance, *Wald* $\chi^2(1) = 0.01$, $p = .92$, and tree processing time, *Wald* $\chi^2(1) = 1.21$, $p =.269$, were not. The overall Model 1 was significant compared to the intercept-only model, $\chi^2(5) = 22.086$, $p = .001$ (see Table 2, Model 1 for parameter estimates).

In order to find out and clarify the effect of hierarchical complexity measure alone, we standardized the hierarchical complexity measure[4], as the task did not have a time limit. In the second model (Model 2, *n* = 46), the factors age group, *Wald* $\chi^2(1) = 63.074$, $p \leq .0001$, and tool manipulation, *Wald* $\chi^2(1) = 75.027$, $p \leq .0001$, and the covariate standardized hierarchical complexity, *Wald* $\chi^2(1) = 6.803$, $p = .009$, were significant predictors of tool making scores. The overall model was significant compared to the intercept-only model, *Wald* $\chi^2(3) =21.744$, $p \leq .0001$ (see Table 2, Model 2 for parameter estimates).

In the third model (Model 3, *n* = 43), test of model effect results demonstrated that the factors age group, *Wald* $\chi^2(1) = 34.904$, $p \leq .0001$, and tool manipulation, *Wald* $\chi^2(1) = 79.696$, $p \leq .0001$, and the covariate inhibition latency, *Wald* $\chi^2(1) = 6.812$, $p = .009$, were significant predictors of tool making. Model 3 was significantly different from the intercept-only model, $\chi^2(2) = 22.444$, $p \leq .0001$ (see Table 2, Model 3 for parameter estimates).

When comparing children who had failed in the inhibition task (inhibition task error, *n* = 7), namely the ones who used a response strategy (see the 'Coding, Data Analysis and Data Reduction') among those who passed it (*n* = 43) a significant relation was found between these two groups and their tool making scores, *FET*, $p = .048$. The children who failed in the inhibition task had lower scores and those who did not fail had higher scores. Besides, the children who had problems with

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[4] The standardized values were calculated according to the following equation: standardized hierarchical complexity = (hierarchical complexity * grant mean of the tree structuring processing time)/(tree structuring processing time)

the *hierarchical tree structure task* (tree task error, *n* = 4) had significantly lower scores than those who did not have problems with the task (*n* = 46), *FET*, *p* = .038.

Subsequent follow-up analyses clarified and supported GLM results. There was a significant difference in tool making scores between age groups, *FET*, *p* = .001, φ= .46. 5-6-year-old children obtained significantly higher scores than 3-to-4-year-old children. All subsequent analyses were computed only for the 3-to-4-year-old age group, since all the 5-to-6-year-olds obtained only the high score (score 2). However, see Appendix A Supplementary Material 4 for the analyses with the full sample size, which indicated very similar results. Bonferroni corrected *p* values were used (*p* = .025) for the subsequent analyses.

Hierarchical complexity differed significantly between children who obtained low tool making scores (*n* = 9, *M* = 45.67) and those who obtained high tool making scores (*n* = 17, *M* = 61.94), *t* (23.581) = -2.655, 95% CI [-28.939, -3.61], *p* = .014, Gates' *delta* = .17; however, hierarchical resemblance, *t*(24) = -0.772, *p* = .448, and tree structuring processing time, *t*(24) = 0.694, *p* = .50, were not significantly different between these two groups. Also standardized hierarchical complexity between children who obtained low tool making scores (*n* = 9, *M* = 40.46) and those who obtained high tool making scores (*n* = 17, *M* = 66.23) were significantly different, *t* (22.563) = -2.709, 95% CI [-45.47, -6.07], *p* = .013, Gates' *delta* = .20. Inhibition latency was significantly longer in the low tool making score group (*n* = 8, *M* = 1934) than in the high tool making score group (*n* = 14, *M* = 1355), *t* (20) = 2.986, 95% CI [175, 984], *p* = .009, Hedges' *g* = .13. Although there is no significant relation between tool manipulation and tool making scores, *FET*, *p* = .066, this relation reaches significance if an ordinal direction is assumed for the tool making scores, *Somer's d* = 352, *p* = .01.

Table 2: Parameter Estimates of the GLM Models

Model-1 *

			Hypothesis Test		
Parameter	*B*	*SE*	*Wald* χ^2	*df*	*p*
(Intercept)	-1.772	1.383	1.642	1	.200
Age groups: 5-to-6-year-old	3.962	0.565	49.216	1	≤.0001
Tool manipulation: tool manipulators	3.881	0.507	58.678	1	≤.0001
Hierarchical complexity	0.047	.020	5.310	1	.021
Hierarchical resemblance	-0.014	.135	.010	1	.920
Tree processing time	-0.010	.009	1.220	1	.269
Model-2*					
(Intercept)	-1.743	.837	4.334	1	.037
Age groups: 5-to-6-year-old	3.760	.473	63.074	1	≤.0001
Tool manipulation: tool manipulators	3.657	4.221	75.027	1	≤.0001
Hierarchical complexity (standardized)	0.03	.0117	6.803	1	.009
Model-3 *					
(Intercept)	3.061	1.145	7.153	1	.007
Age groups: 5-to-6-year-old	4.846	.789	37.741	1	≤.0001
Inhibition latency	-0.002	.001	6.901	1	.009

*Fisher scoring parameter estimation method was used. Robust estimator was used for the covariance matrix (see, Agresti, 2015; Stroup, 2013). The reference category of the dependent variable (tool making scores) was the lower value (score 1).

3.5. Experiment 1: Discussion

This study aimed to reveal the cognitive bases of tool making in terms of executive control (response inhibition) and hierarchical structuring in 3- and 4-year-old and 5- and 6-year-old preschool children. The results showed that children's age, tool manipulation ability, hierarchical complexity, and inhibition latency predicted tool-making scores (tool making after social learning) of the preschool children. Overall, children had great difficulty in tool innovation; however, in particular, older children could make a hook to solve the task after observing the tool being made by an adult, which illustrates the power of social learning in tool making.

3.5.1. Understanding the demands of the task and tool use

Our first-touch results showed that whereas young children first touched either the pipe cleaner or a piece of string at chance level, most used a pipe cleaner for the hook task later on. This means that they changed their first decision and selected the material compatible with the demands of the task. On the other hand, older children touched the functional tool (pipe cleaner) first and went on using it. We argue that young children are still exploring materials before deciding which of them to use later. However, older children, who have better knowledge about and experience with objects in the world, might perceive the affordance of the tool immediately and select the most appropriate one in advance.

3.5.2. Tool making and social learning

The results showed that, overall, preschool children had great difficulty in tool innovation. Thus, our results replicate numerous similar findings in the recent literature with the hook task (see Beck et al., 2011, 2016; Chappell et al., 2013; Cutting et al., 2011, 2014) or other tasks such as the floating object task (Nielsen, 2013).

The results obtained from Phase 1 showed that tool innovation was very difficult for the young children, and only 1 of the older participants could spontaneously innovate the tool. Legare and Nielsen (2015) stated that more systematic innovation develops with age, and it may be hard to find relations between preschoolers' tool innovation and the cognitive factors triggering it because young children's tool innovation might be more random. Most of the children, however, could make a tool in the second phase. This result indicates the power of social learning in tool making. In this respect, it might be claimed that young children's physical understanding regarding spontaneous tool use inventions might be similar to that of great apes (see Reindl et al., 2016), and it might be our early developing social learning ability that made us better tool makers and users (see Tennie et al., 2009). However, the reasons why great apes and young children fail in tool innovation by changing the shape of a tool, and why tool innovation is rare among young children and great apes, should be investigated in the future.

Whereas all the 5- and 6-year-old children could make the tool and solve the task in Phase 2, some of the younger children were still unable to solve it and most of them could not do this in Phase 3 either. This finding may indicate that mere repetition and perseverance are not sufficient to enhance young children's tool-making performance; the demonstration of the tool making must trigger children's understanding of how the (properties of the) tool used by a human model may help to resolve the task.

3.5.3. Tool making after social demonstration: the effects of age, manipulation, inhibition, and hierarchical structuring

The GLMs and follow-up analyses revealed that age, tool manipulation, inhibition latency, and hierarchical complexity—but not resemblance and tree structuring processing time—could predict tool-making scores significantly. As indicated above, children are known to be good social learners (see also Csibra & Gergely, 2009; Tomasello, 2016). The older children, especially, may have been able to understand the intention and goal of the experimenter when he or she showed how to make the tool. However, another possibility is that children who were successful after social demonstration might have copied only the result; in other words, they may have engaged in result emulation (for different types of social learning, see Whiten, McGuigan, Marshall-Pescini, & Hopper, 2009). In the current study, the following observation is suggestive of result emulation: One child in the older age group copied the action of the experimenter (bent the pipe cleaner) but used the unbent side of the pipe cleaner in the subsequent attempt to retrieve the bucket; about 10 s later, he looked at the bent upper part of the pipe cleaner and then rushed to use it to retrieve the bucket. This observation may illustrate the difference between mere copying behavior and social learning with respect to the goal information. In any case, all the 5- and 6-year-old children could make a tool after the first tool-making action demonstration, but only 60% of the 3- and 4-year-old children could do so.

Tool manipulation—that is, changing the shape of the pipe cleaner yet without making a functional tool in Phase 1—was a significant predictor of tool-making scores in later phases. Six children tried to manipulate the pipe cleaner in Phase 1, but either their manipulation of the material was too coarse or the bent side was too big to fit into the tube, so they could not raise the bucket. All these children were in the 3- and 4-year-old age group, which is in line with the view that young children might be more exploratory than older children (Gopnik, Griffiths, & Lucas, 2015; see also Legare & Nielsen, 2015). All these children were successful in Phase 2. It can be speculated that those children still needed to refine their tool-making performance through social learning, although their tool-making capacity was already clearly observable.

GLM and follow-up test results indicate that inhibition latency was a significant predictor of tool-making scores. Beyond that, children who made a task error in the inhibition task also got low tool-making scores. Considering the constraints on executive function present at these ages, some children might have been able to inhibit their previous unsuccessful responses more and adopt the action they had just learned socially. This explanation is also in line with research showing that social cognition and executive function for response inhibition codevelop in children at those ages (Bjorklund & Kipp, 2002; Perner & Lang, 1999). Beck et al. (2016) did not find a relation between response inhibition and tool innovation in 6- to 8-year-old children in a task similar to that undertaken in the current study. However, their results were focused on tool innovation (Phase 1 results of this study) in older children. Chappell et al. (2013) also reported that prompting children to produce alternative solutions in the hook task does not increase tool innovation success. However, in the current study, we were concerned with the tool making through social learning in a younger population. Beck et al. (2016) also used other executive function tasks related to working memory, attentional flexibility, and ill structured problem solving, none of which predicted spontaneous tool innovation. They concluded that the difficulty encountered by children in spontaneous tool innovation could not be explained by children's executive functions. In our study, however, executive function as measured by response inhibition could predict tool making that occurred mainly in the second phase, that is, after observing how the experimenter manufactured the tool. In such a social setting, children could successfully connect information from the social and technical domains.

As Greenfield and Schneider (1977) argued, children have problems in constructing and copying hierarchical shapes, especially before 5 or 6 years of age, yet the complexity of their shapes resulting from putting units together to form a coherent whole may show their developing capacity for building hierarchical representations. These results may be explained in terms of making part–whole relations and controlling this process consciously. As Mounoud (1996) stated, the ability to form coherent part–whole representations through recursive action—in our case, combining sticks —develops after 5 years of age. From our results, we can conclude that children who were better at making more complex and hierarchical part–whole relations in the hierarchical structuring task were also better at connecting task elements and social information to solve the hook task. One other possibility is that tool making might be related to a more general cognitive capacity such as intelligence. Therefore, future studies may use a measure of intelligence as a control variable. However, note that Muthukrishna, Morgan, and Henrich (2016) found a negative relation between social learning and intelligence.

3.5.4. Tool innovation

Results indicate that spontaneous tool innovation is very rare in preschool children. Rather, children benefitted from social learning and could make and use the tool successfully in subsequent phases of the experiment. Although we found that inhibition latency and hierarchical complexity were positive predictors of tool making after social demonstration, it might be hard to generalize this finding to tool innovation. It should be noted that even the children who were very good in the hierarchical structuring and inhibition tasks could not innovate the tool spontaneously, which may indicate that changes in these cognitive capacities might not be the drivers of tool innovation (see Beck et al., 2016; Chappell et al., 2013). For instance, Chappell et al. (2013) demonstrated that prompting children to find alternative solutions for the task did not improve their tool innovation success. However, that still might not mean that tool innovation does not require inhibition and hierarchical structuring. Although these abilities might be necessary cognitive skills in action control for tool making, they might not be sufficient for innovating a tool spontaneously. We claim that tool innovation might require two critical cognitive abilities: spontaneous creativity/imagination and controlled tool manufacturing. Although children may be able to come up with creative solutions for the hook task, namely the idea of a hook, controlling their actions according to their creative solutions—in other words, their mental simulations of how to implement them—may still be immature. This ability might require multimodal processing of information according to abstract rules (see Klingberg, 2006). The crucial role of multimodal processing in tool making has been emphasized elsewhere (Stout & Chaminade, 2012; Stout, Toth, Schick, Stout, & Hutchins, 2000; Uomini & Meyer, 2013). In this respect, it is interesting that some of the children in Phase 1 of the hook task said that an item like a small hooked cane would work to retrieve the bucket. In addition, 2 participants drew a hook shape with their fingers. However, the children did not attempt to bend the pipe cleaner in this imagined form. Beyond that, as mentioned above, 6 (of the younger) children attempted to manipulate the pipe cleaner in Phase 1, but their tool was not feasible in the hook task. Although children were able to form a mental representation of the proper target tool, namely a hook, they were not able to impose this imagined form onto the concrete tool at hand, the pipe cleaner. The hierarchical structuring task also presupposes imagination and simulation. Yet, some children could not implement their correct mental representations of the target shape at the action level. At the same time, they were aware of and deliberately admitted their incompetence, stating that they could not do this. One of the children frankly told the experimenter that what he made was somewhat similar to the shape he had been shown, but not very similar.

Based on these results, we speculate that although preschool children experience great difficulty in innovating tools, they may come up with creative ideational solutions for the task. They might imagine a tool that could be functional for solving the task; however, they might not be ready to change the shape of a novel tool such as a pipe cleaner according to their mental simulations. If this reasoning is correct, the hook task may be easier for children to accomplish using more familiar tools, which should be investigated in future studies. As Beck et al. (2011) showed, children could solve the innovation problem with the pipe cleaner in the same task only starting from 7 years of age. Seemingly in accordance with their study, the results of the current study—in particular those from Phase 1 (tool innovation) — also suggest that preschoolers until 6 years of age do not have sufficiently developed abilities to innovate tools spontaneously. However, results also show that they could fill this gap with their enhanced social learning ability (Cutting et al., 2011). If the tool-making action is demonstrated to them by an adult in a social learning setting, 5- and 6-year-olds can mostly use this information to solve the problem.

In conclusion, we investigated the effect of response inhibition and hierarchical representation on Turkish preschool children's tool-making abilities. We replicated previous results indicating that children have difficulty in innovating tools spontaneously, and 5- and 6-year-old children were often able to use information provided to them socially to improve their tool-making abilities more than younger children. Beyond that, we showed that inhibition latency and hierarchical complexity competence predicted tool-making scores, as emphasized in the phylogeny literature. Here, we provide evidence that these relations also hold in ontogeny. However, research on the cognitive ontogeny of tool making is still in its infancy. To achieve more ecologically valid results, the cognitive bases of tool making should be investigated considering different tools, different social interactions (e.g., through peer interaction), and different tasks. The effect of different types of social learning on tool making should be investigated; so far, studies on the development of tool making have focused on different types of social demonstration as stated in the Introduction (section 4.2). To learn how tool making is facilitated by different types of social learning, comparisons between these types should be made. Finally, the idea that mental simulation of a feasible tool precedes tool-making action with a novel tool should be carefully tested in the future.

CHAPTER 4

STUDY 2: ONTOGENY OF TOOL MAKING IN CHILDREN: PERCEPTUAL-ACTION AND REPRESENTATIONAL FACTORS[5]

4.1. Abstract

Although other animals can use and make simple tools, the extent and complex material culture of humans is unprecedented in the animal kingdom. How does this capacity for tool making develop? In this study, the perceptual-motor and representational aspects of tool making are investigated with a task in which adults ($N = 20$) and 5-to-6-year-old children ($Ns = 75$) are asked to remove a small bucket from a vertical tube. The results show that while adult tool innovation and selection are based on the tools' salience of affordance, children are better at tool making if the tool and its relation to the task are familiar. Complex hierarchical structuring and divergent thinking in children are further predictors of their tool making ability.

Keywords: Tool making, tool innovation, familiarity, salience of affordance, hierarchical structuring, divergent thinking.

4.2. Introduction

In the literature of ontogeny and phylogeny of tool making, different factors have been highlighted such as perceptual and motor properties (Bates, Carlson-Luden & Bretherton, 1980; Gibson, 1979, 2015; van Leeuwen, Smitsman & van Leeuwen,

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1994; Gibson & Pick, 2000), the type of actions (see Beck, 1980; Oswalt, 1976), hierarchical representation (Greenfield, 1991), flexible creative transfer (Brown, 1990), planning (Cox & Smitsman, 2006), design understanding (Defeyter & German, 2003), insightful problem solving (Köhler, 1957), executive function and response inhibition (Coolidge & Wynn, 2005), and social cognition (Tomasello et al., 2005). Rather than specific factors, it might be the case that interaction between various factors made human tool culture spread widely (Vaesen, 2012). In the last decade a hybrid approach as an alternative has become prominent. In this approach, perception-action as well as representational mechanisms function as feedback during tool use (see Greif & Needham, 2011; Deàk, 2014; for adults see, Osiurak, Jarry & Gall, 2010). According to this approach, infants and children learn action possibilities with exploration, using objects. While this learning process is more perception-oriented in the earlier stages of life, it becomes more conceptual as the child learns causal relations between actions and their outcomes in tool use. Learning the perceptual-motor properties of the tools contributes to constructing causal structures with tools, and thus, these causal relations directly affect future interactions with tools. As a result of this feedback between perceptual-motor and conceptual factors, infants become more proficient in using tools in different environments and their functional tool knowledge gradually increases (see, Greif & Needham, 2011). Beyond perceptual-motor factors, Deàk (2014) also lays emphasis on social learning during the process of learning tool functions, in which children acquire the intended functions of tools, especially after the age of two. Based on the ontogeny and phylogeny literature, in this study we investigate the effect of perceptual-motor (familiarity and salience of affordance), representational (hierarchical complexity), creative factors (divergent thinking) and their interaction on tool making ability of preschool children.

4.3.1. Tool use

Beginning from early months, infants are able to use tools (such as a spoon) with a specific aim (Connolly & Dalgeish, 1989), or to reach a target through seeing the complementary relation between the tool and the target, such as fetching a toy with a stick, especially after the first year of age (McCarty, Clifton, & Collard, 1999; Bates, Carlson-Luden, & Bretherton, 1980). Infants and children may learn how to use tools from different sources, e.g. exploration or observation (Gardiner et al., 2012; Somogyi et al., 2015). Although tool use is an early developing skill, preschool children are poor at some types of tool-related behavior, in particular tool innovation. In other words, children are not ready to make novel tools spontaneously until the end of their seventh year (Beck et al., 2011).

Why do children start to make novel tools later? Piaget (1970; 1964) claims that children in the 'preoperational' stage (3 to 4 years) begin to construct abstract representational thought to solve problems related to tools. Then, in the ''concrete operations'' stage, children (aged 5 to 7) improve in applying abstract constructions pertinent to the world. Thus, the child can hold in their mind both the parts and the whole of the objects, and start to connect them spontaneously after 7 years of age. On the other hand, Mounoud (1996) stated that whereas 3- to 4-year-olds employed previous knowledge sources when constructing new knowledge, 4- to 5-year-olds were able to build new elementary representations onto their previous knowledge while making novel tools. Five- to 7-year-olds start to go beyond new elementary representations and concatenate them to form global representations so that they can solve new problems recursively; however children make better recursive part-whole relations only after the age of seven. Do experimental studies on the development of tool making support these claims?

4.3.2. Tool making and tool innovation

According to Cutting et al. (2011) and Nielsen et al. (2014), tool making comprises two levels: First is tool innovation, in which the modification or alternative use of the tool is revealed in the agent, and second is tool manufacture, in which the agent makes the tool after a demonstration of the ready-made-tool or the activity of tool making itself. The spontaneous production of a novel tool is very difficult for children before the age of seven or eight. The hook task, in which children were required to bend a pipe cleaner and retrieve a bucket from a long vertical tube to obtain a sticker, proved to be very difficult for preschool children. They could solve this task only after observing how to manipulate the tool properly or seeing the ready-made tool; that is, it relied on social learning (Beck et al., 2011; Cutting, Apperly, & Beck, 2011). These results might indicate the crucial role of social learning on children's tool making. In support of this opinion, some researchers put forward to our social learning ability rather than individual innovations (see Buttelmann, Carpenter, Call & Tomasello, 2008; Price, Caldwell, & Whiten, 2009).

Although most pre-school children can easily understand the goal and select the proper tool (e.g. a bent pipe cleaner), they have a great difficulty in creating a tool spontaneously (a hook in this case). Subsequent studies showed that this difficulty cannot be explained by lack of executive functions and divergent thinking capacity (Beck et al., 2016). However, cognitive/representational might facilitate tool making after social demonstration, in other words they may affect tool manufacture in preschool children (Gönül, Takmaz, Hohenberger, & Corballis, 2018). On the other hand, preschool children's difficulty in tool innovation might stem also from their insufficient knowledge of the world (Legare & Nielsen, 2015). In this case, perceptual/motor factors might facilitate their tool innovation (Neldner, Mushin, & Nielsen, 2017), or these factors might also facilitate tool manufacture, which is also considered in this study.

4.3.3. Tool making: familiarity and affordance

Studies clearly demonstrate that prior experience and familiarity are crucial factors in tool use in infants and children (Greif & Needham, 2011; Barrett, Davis & Needham, 2007). However, beginning from the first year, children learn how to use some tools in a demarcated context, such as a spoon for eating. Thus, prior experience and familiarity might also be a limiting factor for using tools in novel situations. For instance, Barrett, Davis and Needham (2007) show that 12-to-18-month-old infants are better at solving a new problem using a novel tool compared to a familiar tool – a spoon.

As stated above, even though children are good at using ready-made tools, making a novel tool (e.g., by changing its shape) to solve a task is challenging for children up to the age of seven (Cutting et al., 2011; Nielsen et al., 2014). Recent studies indicated that becoming familiar with the properties of a tool facilitates spontaneous tool innovation, e.g. seeing a hooked tool before solving the hook task (Whalley, Cutting, & Beck, 2017), and making the affordance of the tool clearer eases tool making in preschool children (Neldner, Mushin, & Nielsen, 2017). However, adults can go beyond the familiarity of the tools and infer the affordance relations of a tool for a particular problem (Osiurak, 2010).

4.3.4. Representational and creative factors in tool making: Hierarchical complexity and divergent thinking

Hierarchical representation ability is considered to be one of the most crucial factors for making tools (Stout, 2011) and Greenfield (1991) claims that the expansion of prefrontal cortex during evolution provided the basis for the mastery of hierarchically complex manual combinations, which in turn might have provided the basis for the evolution of tool-related behaviors and technical understanding. More generally, it is claimed that one of the distinctive capacities of human cognition is the ability to form higher-level representations necessary for imitating hierarchically structured patterns and actions (Langer, 1998; Greenfield, 1991). Children who are better in constructing hierarchically complex shapes might also be good at in making the relation between the tools, task, and social information in the hook task (Gönül, Takmaz, Hohenberger, & Corballis, 2018). Greenfield and Schneider (1977) show that children become better at making hierarchically complex tree-like constructions with small sticks after age five and six. In their study, the term of hierarchical complexity is operationalized based on graph theory, which is also adopted in this study. Constructing complex hierarchical representations might be crucial for both hierarchical structuring, in which sequencing actions according to hierarchical shapes is required (Greenfield and Schneider, 1977; Greenfield, 1991), and tool making and innovation in which ′′increasing hierarchical complexity in turn favours the emergence of technical innovations by providing greater latitude for the recombination of action elements and sub-assemblies′′ (Stout, 2011; p.1055). Beyond constructing elements, hierarchical representation might also facilitate social learning (Byrne & Russon, 1998). For instance children can overcome complex tool use problems if their level of information is systematically increased, for example by watching an older person demonstrating complex action patterns with the tool in a hierarchically organized way (Flynn & Whiten, 2008a).

Greenfield and Schneider (1977) connect their argument concerning the ability to make hierarchical constructions with Piaget's work (1951), claiming that older preschool and young school children can create transformative part-and-whole relations. Mounoud (1996) refers to this knowledge transformation in children aged 5-to-7 as a recursive activity, in which practical (e.g., perception-action related) and conceptual forms of knowledge conspire to form "hierarchical and fairly complex relations that reverse over time′′ (p. 96); however, spontaneous transformation of conceptual knowledge for the recursive part-whole relations develops after the 7-years-of-age. At this point, it can be asserted that children aged 5-to-7 can go beyond making complex hierarchical representations in that they apply them to new situations (Callahan, 2013); thus, enhancing their creativity and divergent thinking. Corballis (2014) has indeed emphasized that it is our ability for hierarchical structuring and recursion that allows us to use and make tools in an innovative and creative way.

A common way to assess creativity is through "divergent thinking". Although divergent thinking is a part of creativity, these two terms are not identical. Generation of ideas and going beyond immediate perceptual factors might be the distinguishing feature of divergent thinking. However, even though a person might be able to think divergently, it may not lead to creative products (Runco & Acar, 2012). On the other hand, while divergent thinking requires generating alternative solutions, tool innovation requires applying specific functional solutions to the problem such as changing the shape of a tool or using a tool in alternative ways individually. In their framework of tool innovation, Carr, Kendal and Flynn (2016) claim that divergent thinking is one of the facilitating factors for tool innovation. Generation of novel connections and coming up with original ideas might be crucial both for innovation (and tool making in general) and divergent thinking. Even though divergent thinking was not found to be a significant predictor of tool innovation in the developmental study conducted by Beck et al. (2016), divergent thinking might still be essential in tool making (Deacon, 1997; Mithen, 2003) if it is understood as a process comprising exploration and social learning.

4.3.5. This study

Focusing on only some specific factors might not be enough to explain why human material culture is more flexible than tool-related behaviors found in other animals (Vaesen, 2012). Therefore, it might be crucial to consider the complex interaction between various factors to understand why human tool-related behaviors are flexible and so widespread (see, Stout, 2011; Vaesen, 2012). How do perceptual-motor factors, as well as representational and creative factors affect the tool making? As most adults have sufficient knowledge of the world and an adequate technical understanding of complex affordance relations (Osiurak, Jarry & Gall, 2010), it can be predicted that adult tool making and tool selection are based on the salience of the affordance of the tool (to what extent the tool seems relevant to solving the novel task). However, unlike adults, 5-to-6-year-old children may be proficient at making tools only with familiar tool-task relations. On the other hand, children's capacity for making hierarchically complex structures (tapping their hierarchical representation capacity) and divergent thinking (as an indicator of creativity, see Runco & Acar, 2012) can predict their tool making process, as has been emphasized in the phylogeny of tool making literature (Greenfield, 1991; Mithen, 2003).

In this study, we focus on the tool making abilities of 5-to-6-year-old children, as this age range seems to be a transition period for tool making and novel tool construction (see Beck et al., 2011; Mounoud, 1996; Greenfield, 1991). Although 5-to-6-year-old children may not be ready for tool innovation, the tool making process might be facilitated by the familiarity of the tool-task relation or their competence in making complex hierarchical constructions and divergent thinking. In this study, therefore, we focus on tool making as a process, ranging from tool innovation to tool manufacture.

We report two studies: The first is a preparatory study with adults, and aims to evaluate the familiarity and the salience of the affordance of three tools (pipe cleaner, bendable straw, wooden sticks) in the hook task. The results are then considered in the design and interpretation of the second experiment with children, in which the same tools are used. We also assessed representational and creativity factors as predictors of the children's performance in the second study.

4.3. Experiment 2

In the first study, we investigated tool selection in adults as well as the salience of the tools employed and familiarity with three tools in the *hook task*. This task was first used by Hunt and Gray (2002) and Weir, Chappell and Kacelnik (2002) with crows, and by Cutting, Apperly and Beck (2011) with children. The tools utilized in our first study were a pipe cleaner, a bendable (soda) straw, and two wooden sticks, one long, one short, which could be combined into a hook – the target tool.

4.3.1. Method

4.3.1.1. Participants

Twenty people participated in the study (10 women, M_{age} = 29 years) from Middle East Technical University, Ankara. They were all native speakers of Turkish.

4.3.1.2. Materials

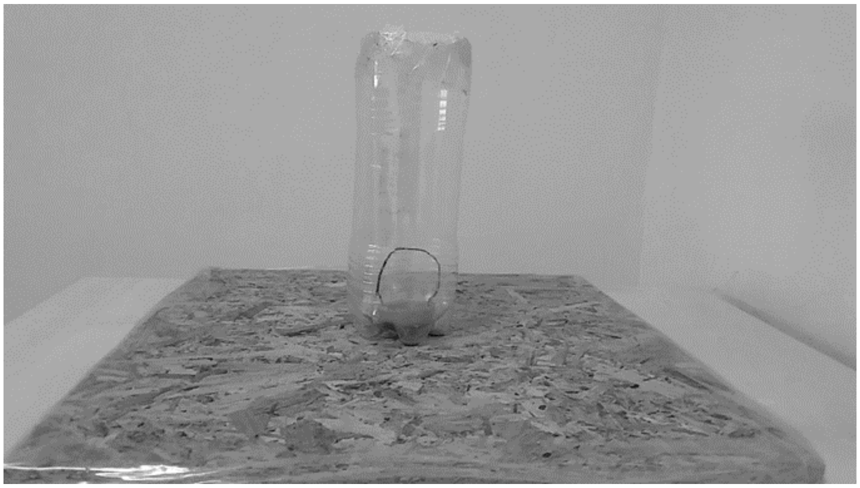


Figure 20: Hook task (experiment with adults)

For the evaluation of the tool making abilities, the hook task ("bending"-task, see Cutting, Apperly and Beck, 2011) was used. For this task, a 16-cm tall transparent plastic tube with a 6-cm wide opening (which is partially) was used. The opening at the top was partially closed by a 6-cm cardboard circle with a 4-cm internal opening. This tube was vertically stuck onto a square wooden board with 30 cm edges. Inside, at the bottom of this tube, there was a small bucket of 1 cm depth, 3.2 cm diameter and a 9.5 cm long handle (see Figure 20).

Three types of tools were used in the study: a pipe cleaner (length = 29 cm), a bendable straw (length = 22 cm) and a long wooden stick (length = 27.5 cm, diameter = 1.5 cm) with two holes (diameter = 0.7 cm) that were 1.5 cm from the both end points. One side of the straw (soda straw) had a 1 cm flexible and bendable part that was 2 cm below the end point. The long stick was presented together with a 3.5 cm short stick. The surface of the short stick was knurled (around 0.1 cm), which made the short stick perfectly fit into the holes in the long stick without much effort (See Figure 21).

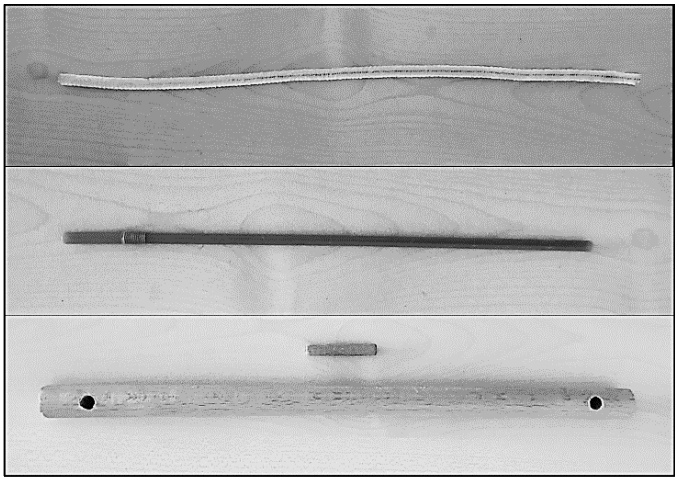


Figure 21: Pipe cleaner (top), bendable straw (middle) and wooden sticks (bottom)

4.3.1.3. Procedure and coding

Each participant and the experimenter sat across a desk from each other in a quiet room. The tools and the task were presented to the participants (the order of the tools was counterbalanced across participants). The participants were assured that there was no trick in the study. Firstly, they were asked to touch all of the tools one by one (10 seconds). The participants were asked to retrieve a small bucket from a long horizontal tube (See, Cutting, Apperly and Beck, 2011; Cutting, 2013) using a pipe cleaner, a bendable (soda) straw or a long wooden stick with a short stick (Figure 20 and Figure 21). They were expected to bend the pipe cleaner or the straw, or combine the wooden sticks into a hook shape to remove the bucket. After the participants achieved the goal of the task, they were asked to try to solve the task with the tools other than the one in which they first solved the task. Then, the participants evaluated the saliency of affordance of the tools from 3 (high salience) to 1 (low salience) by answering the question: 'which tool was the most salient and the most suitable one to solve the task?' After the participants ordered the tools in terms of salience of affordance, they were also asked to order the tools in terms of familiarity, again from 3 to 1.

4.3.2. Results

All the participants manipulated the tools appropriately before inserting them into the tube. Most of the participants selected the pipe cleaner (55%), a smaller number chose the wooden sticks (35%), and the remaining participants (10%) selected the bendable straw first. Cochran Q test results showed that these proportions were significantly different, $\chi^2(2) = 6.1$, $p = .047$, $\eta^2_Q = .15$ (Figure 22). Friedman's ANOVA results indicated that the pipe cleaner was evaluated as more salient for the task than the wooden sticks and the bendable straw, and the overall difference between the tools was significant, $\chi^2(2) = 6.4$, $p = .041$ (Figure 22) ($r = .29$, $-.63$, and $.29$ for BC vs WS, PC vs BS, and WS vs PC, respectively). Furthermore, there was a significant positive Kendall's *tau* correlation (two-tailed) between the first tool selection and the most salient tool, $\tau = .54$, $p = .003$. Finally, Friedman's ANOVA results showed that there was a significant overall difference in familiarity between tools, $\chi^2(2) = 32.4$, $p = .0001$; the straw was evaluated as more familiar than the wooden sticks ($r = -.76$) and the pipe cleaner ($r = -.93$), and similarly, wooden sticks were evaluated to be more familiar than the pipe cleaner ($r = -.79$). All the significant adjusted pairwise comparisons are shown in Figure 22.

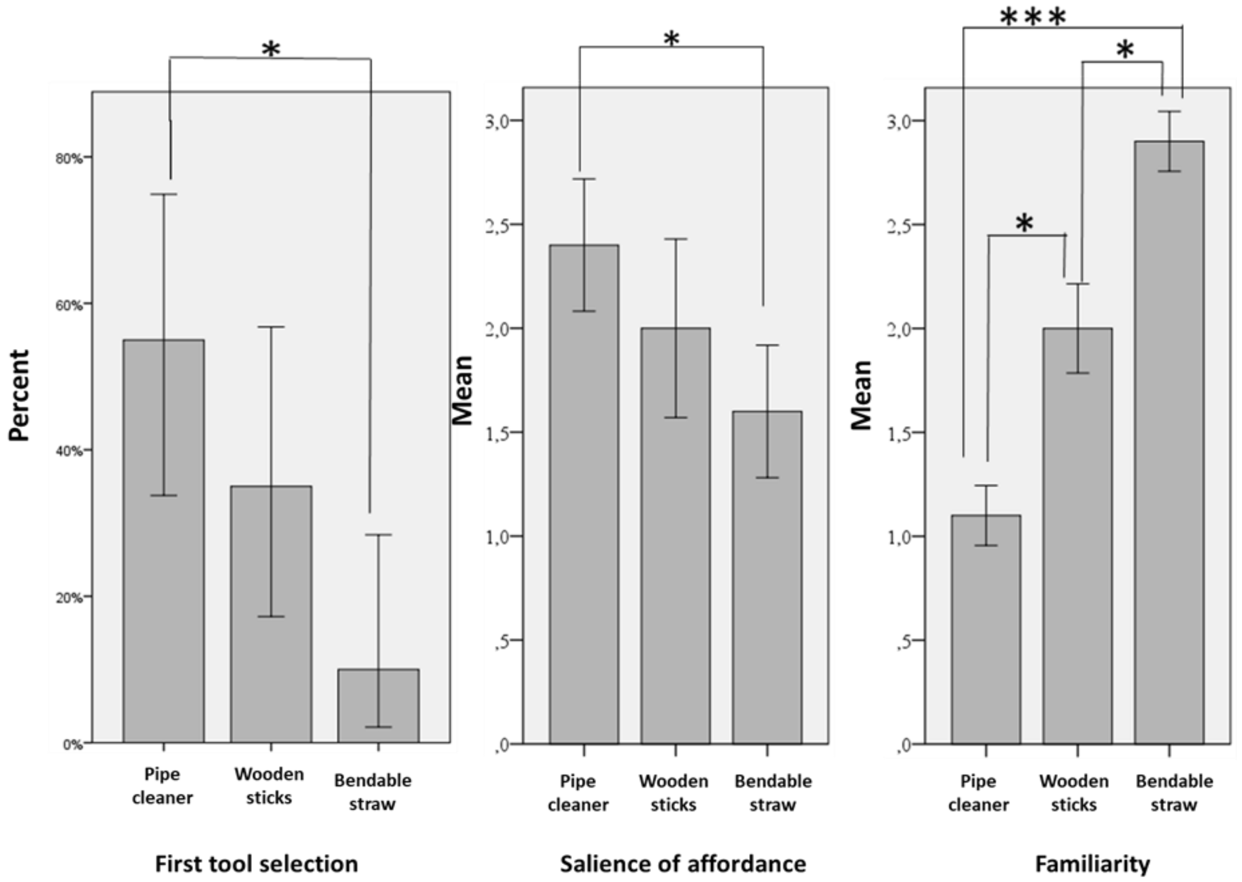


Figure 22: Graphs based on the study with adults. Error bars show 95 % Confidence Intervals. Asterisks show significant corrected pairwise comparisons between groups (*p ≤ .05, **p ≤ .01, ***p ≤ .001).

4.4. Experiment 3

As stated in the introduction, the first step of tool making is called ‘tool innovation’ and children have great difficulty until the age of 7-8 in spontaneous tool innovation. However, children can make tools, if a ready-made tool or the tool making action is demonstrated without giving information about the goal. Hence, in this second study, we included various phases of tool making in which tool making is facilitated through phases in an ordinal way.

4.4.1. Method

4.4.1.1 Participants

Based on the results of the first study, in order to observe the effect of perception and action dimensions (familiarity and salience of affordance) and representational capabilities regarding children's tool making ability, 75 children from Ankara and Muğla, Turkey, all attending kindergartens, participated in the study and they were randomly assigned to one of the following groups according to the material made available: Pipe Cleaner (PC) ($n = 23$, 11 girls, $M_{age} = 68$ months 1 week, *Range* = 59-79 months), Bendable Straw (BS) ($n = 25$, 10 girls, $M_{age} = 68$ months 1 week, *Range* = 63-76 months), and Wooden Sticks (WS) ($n = 27$, 11 girls, $M_{age} = 68$ months 2 weeks, *Range* = 60-81 months). See Figure 21 for the materials and groups. Two additional children who were able to solve the hook task without making a tool were excluded. Participants were tested in a quiet room in their kindergarten by a male (G.G.) or female (E.K.T.) experimenter. Before the experiment, the kindergarten teachers asked children not to tell about the game to other children in order to make the game a surprise for everyone. The data were collected at the end of 2015 and the beginning of 2016. We conducted a pilot study prior to experiments with 7 additional children. Please see Appendix B Supplementary Material 1 for the details of the pilot study.

4.4.1.2. Materials, experimental design and procedure

There were three tasks in the study. All the children performed the hook task and the hierarchical structuring task; however, only the children in the wooden sticks group also performed the divergent thinking task (See Figure 23).

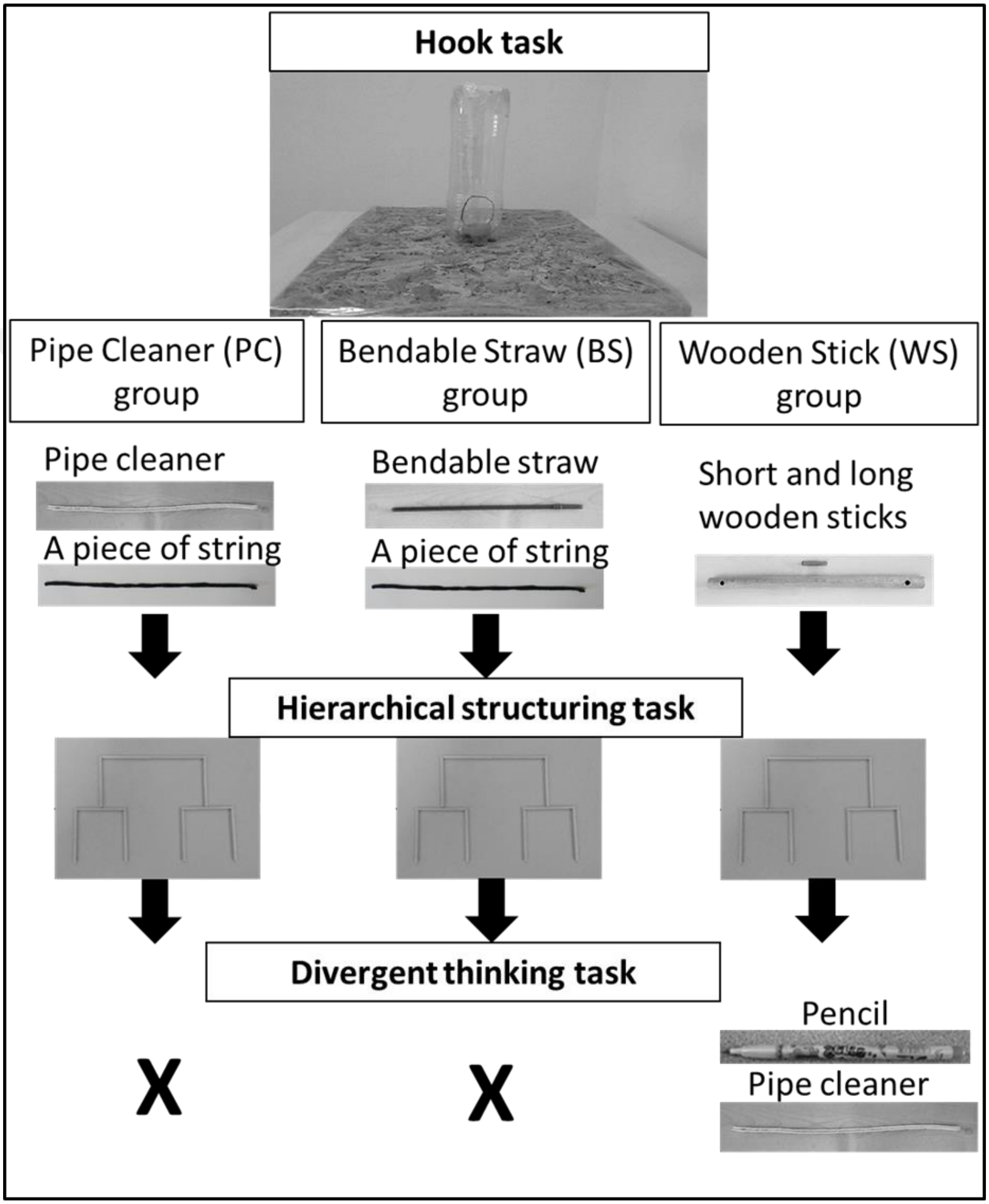


Figure 23: The design and the materials of the Experiment 3 according to three groups. Arrows indicate the order of the material during experiment.

4.4.1.2.1. HOOK TASK

There were three groups of children according to the tool they received (the same tools as in Experiment 2): pipe cleaner (PC), bendable straw (BS), and wooden sticks (WS). The hook task was the same as the one in the first study. A piece of string was also given only to the PC and BS groups to present them with a similar (but non-functional) tool of less rigidity. A piece of string was not used in WS group to keep the number of tools the same in each group. The height of the bottle was 22 cm for the BS group and 29 cm for the PC and WS groups.

After the children were introduced to the *hook task* described above, the experimenter said ''If you get the sticker, you can have it". Then, the tools were brought out by the experimenter and the experimenter said "you can use these ones". Participants had one minute to solve the task (Phase 1, tool innovation phase). If the children could not solve the task in the first phase, the experimenter encouraged them to put the materials down on the board and then showed a ready-made functional tool (a hooked tool). Again, the children were encouraged to solve the task and they were given 30 seconds (Phase 2, tool making after observing the ready-made tool). If they still could not solve the task, the experimenter demonstrated how to make a hook with the tool and the children were given 30 seconds (Phase 3, tool making after observing action demonstration). Note that the experimenter did not show how to solve the task in any of the phases.

4.4.1.2.2. HIERARCHICAL STRUCTURING TASK

In this task, children were asked to engage in a simplified version of the *hierarchical structuring task* (Greenfield & Schneider, 1977), in which they needed to copy a tree-like shape with sticks. An A4-size photo of the end-state of the tree-like shape was shown during this task. Children were given 10 pieces of 4-cm long sticks (similar to matchsticks) and asked to copy the same shape on the table.

4.4.1.2.3. DIVERGENT THINKING TASK

Children in the wooden sticks group were asked to perform an adapted *divergent thinking task* (Guilford et al., 1978), in which a 29-cm pipe-cleaner (as an unfamiliar object) and a 15-cm pencil (a familiar object) were used. In this task, alternative uses of a pencil and a pipe cleaner were asked. Note that only the children in WS group performed this task and they did not perform the hook task with the pipe cleaner and the pencil. In other words, this task was independent of the tool making task. Firstly, the experimenter brought out the tool (a pipe cleaner or a pencil) in front of the children. Children were asked to handle it and check its shape briefly. Then, they were asked: "Can you please tell me what you can do with it?" After every response, children were praised and their responses were repeated by the experimenter: "Yes, very good, you can do … with it, what else?" As this is not an easy task for children (see the pilot study, Appendix B Supplementary Material 1), they were continually prompted with different questions such as "what else can you do with it? How can you use it differently? How can you play with it differently?" If the children were stuck and kept on saying similar things (e.g. for the pencil, ''I can draw with it'', ''I can draw shapes with it''), the experimenter motivated the children to say alternative things (e.g., ''except for drawing and writing, what else can you do with it?''). They were given 1 minute for each material.

This task was not performed by the other two groups since the task results would be impinged upon by the straw and pipe cleaner tools used by children during the hook task. Alternatively, a pencil is used instead of a bendable straw as the properties of the bendable straw might affect the results of the divergent thinking task of the pipe cleaner (given the fact that both of them are bendable). See Figure 23 for the design of the study and groups.

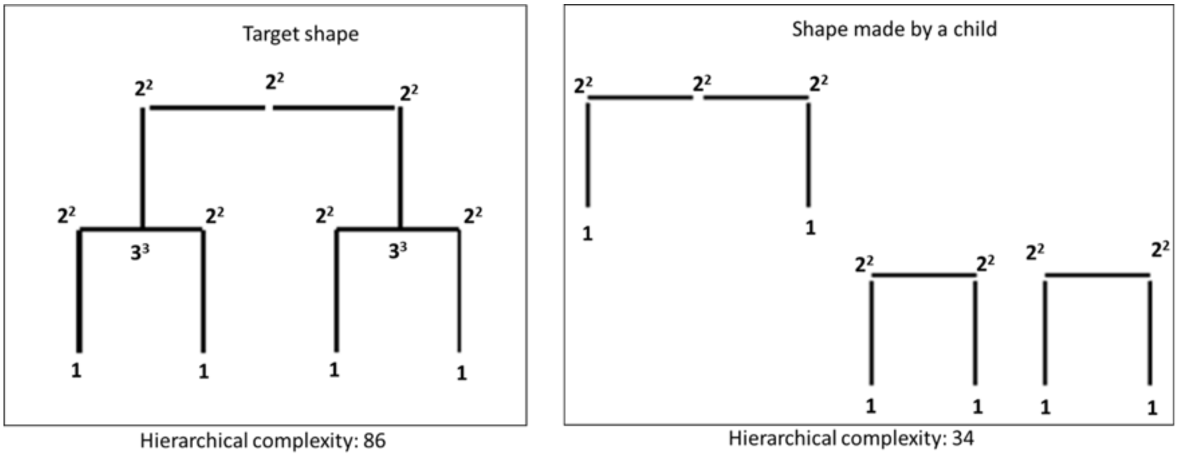
4.4.1.3. Coding and data reduction

The measures of success in tool making, hierarchical complexity and divergent thinking (sum of the enumerated categories) were the scores obtained in these tasks. In the hook task, children could get descending ordinal scores from 4 to 1 according to their success in one of the three phases or in none of the phases (Phase 1, Phase 2, Phase 3, none of the phases), respectively. The reason why we gave descending ordinal scores was that spontaneous novel tool making (tool innovation) is cognitively demanding for preschool children (Nielsen et al., 2014), but their tool making can be facilitated by a showing an end-state tool, Phase 2, (see Chappell, Cutting, Apperly, and Beck, 2013) or a tool making action demonstration, Phase 3, (Cutting, Apperly, & Beck, 2011). However, prior to the main analyses, we checked whether there is any difference between groups in each phase to be able to compare our results with the literature. Tool making success criteria was to create a hook and raise the bucket with the hook. The hierarchical complexity measure was computed based on graph theory (Greenfield and Schneider, 1977) in which a score was given to each node according to the number of units in each node. The scores that can be taken from one, two and three units are 1, 2^2, 3^2, respectively. The only difference in our measure concerned the middle junction, for which children could obtain a score of 3^3 (see Figure 24). Please see Appendix B Supplementary Material 2 for some hierarchical structures made by children.

For the divergent thinking task, first, all the responses were coded. Then, two experimenters (G.G. and E.K.T.) counted the total number of categories for each child. For example, making a triangle, square or a circle with the pipe cleaner is evaluated as one category (geometrical shapes). This coding is known as 'ideational flexibility' (Runco, 1986). Here, it is simply called divergent thinking. Inter-rater reliability was very high between the two coders for both of the tools (pipe cleaner and pen, Cronbach's α = .99, and .96, respectively) for divergent thinking. Six cases of incompatibility were resolved through discussion. Note that two coders discussed the possible categories from the pilot study, but coded the experimental data independently.

As the tool making scores in all three groups violated the assumption of normality (see Table 4 for the normality test results), and the scores were ordinal, we used a Generalized Linear Model (GLM) (McCullagh & Nelder, 1983), since it has greater power than General Linear Models to identify the effects in the model if the distribution is non-normal (Stroup, 2013; NG & Cribbie, 2016). Explanatory tests before, and follow-up tests after the main GLM models were calculated.

The data of the hierarchical structuring task of one child in the PC group were excluded, since she refused to do the task. Two children's divergent thinking data were excluded (1 experimenter error, 1 excessive shyness).



Hierarchical complexity: 86

Hierarchical complexity: 34

Figure 24: Schematic drawing of the target (left) and an example (right) shape

4.4.2. Results

Results showed that tool making success was not significantly different between groups in Phase 1, $n = 74$, $\chi^2(2) = 3.358$, $p = .187$, *Cramer's V* = .21 (data of the successful tool makers in any previous phase were excluded from the subsequent phases). However, Phase 2 success was significantly different between groups, $n = 54$, $\chi^2(2) = 6.093$, $p = .048$, *Cramer's V* = .336. Phase 3 success among groups was approaching significance, $n = 29$, *FET*, $p = .056$, with a large effect size, *Cramer's V* = .431. Children were better in tool making after social demonstration if they used a bendable straw or pipe cleaner (see Table 3). Note that tool making scores were used for the subsequent analyses [descending ordinal scores from 4 to 1 according to their success (Phase 1, Phase 2, Phase 3, or none of the phases, respectively].

Table 3: Success of Tool Making in Phases between Groups

Groups		*Success*			
		Successful			Unsuccessful
	N	Phase 1	Phase 2	Phase 3	
Pipe Cleaner (PC)	23	4	11	7	1
Bendable Straw (BS)	25	9	10	4	2
Wooden Sticks	27	5	7	8	7

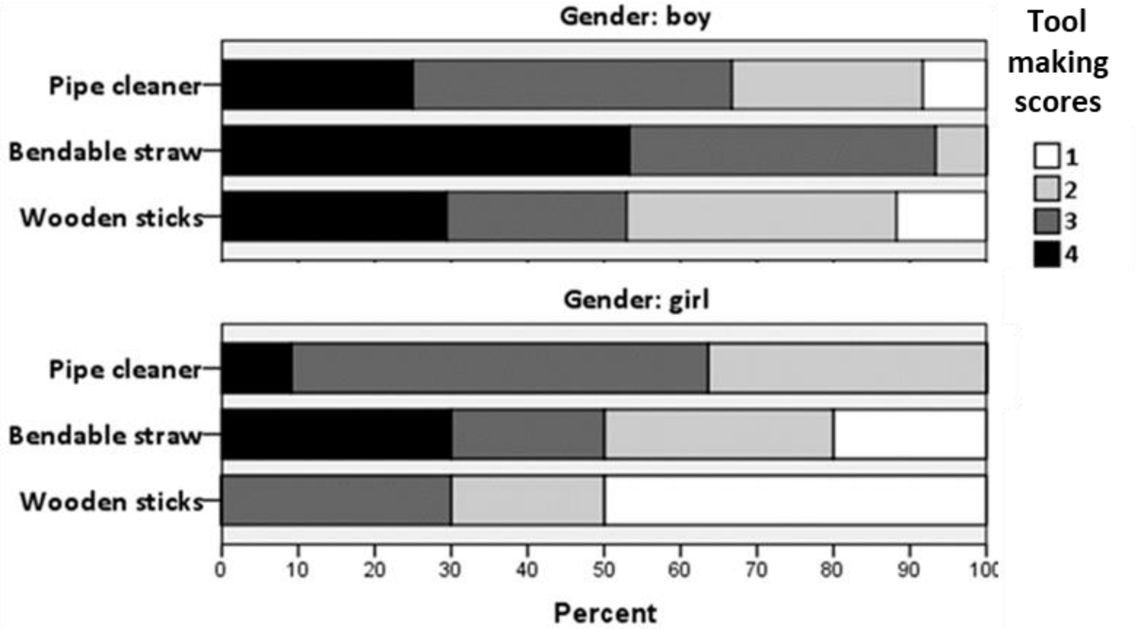


Figure 25: Percentages of tool making scores of boys and girls in the three task groups.

A preliminary analysis in terms of gender showed that boys obtained significantly higher tool making scores (*Mdn* = 43.23) than girls (*Mdn* = 30.58), *U* = 452, *p* = .01, *r* = -.297, in the hook task (see Figure 25). However, the hierarchical complexity results were not significantly different between genders, *U* = 545, *p* = .099. Although we did not have a specific prediction regarding the gender effect, this unexpected finding is discussed in the last section. Gender was included in the main GLM models.

Kruskal-Wallis Test results showed that tool making scores were significantly different between groups, *H*(2) = 7.185, *p* = .028, with a mean rank for 46.06 for the BS group, 39.04 for the PC group, and 30.5 for the WS group (see Figure 25). Pairwise comparisons indicated an adjusted significant difference between BS and WS (*p* = .022, *r* = .37), but not between BS and PC, *p* = .55, *r* = .19, and PC and WS, *p* = .61, *r* = .18.

A Wilcoxon Signed-Ranks Test indicated that divergent thinking was higher with pipe cleaner (*M* = 3.2, *SD* = 1.41) than with pencil (*M* = 1.88, *SD* = 0.88), *Z* = 30, $p \leq .0001$, *r* = -.70. However, considering the relatively small sample size in the divergent thinking task (*n* = 25), sum of divergent thinking results of the tools (pencil and pipe cleaner) was calculated for each child, and used for the subsequent analyses.

Hierarchical complexity results were not significantly different between groups, *H*(2) = 2.167, *p* = .338. Divergent thinking results (only in the WS group) were not significantly different between girls and boys, *t*(23) = -0.061, *p* = .95. Divergent thinking and hierarchical complexity were not significantly correlated in the WS group, $r_s = .101$, *p* = .63 (see Table 4 for descriptive statistics).

4.4.2.1. *Predictors of tool making scores*

In the model, factors, covariates and the interactions were specified based on the results described above and the aims of the study. As for the choice of the link function, we compared different link functions based on *BIC* scores and *deviance value* results (see Appendix B Supplementary Material 3 – Table 8 – for model comparisons) (Raftery, 1995; NG & Cribbie, 2016).

A GLM with a multinomial (ordinal) distribution and complementary log-log link function was calculated to predict descending (from 4 to 3, 2, 1) tool making scores

(n = 74). Hybrid approach used for parameter estimation and robust estimator used for covariance matrix (see Agresti, 2015). Tests of model effect results demonstrated that the factor group, *Wald* $\chi^2(2)$ = 16.954, p = .0002, the factor gender, *Wald* $\chi^2(1)$ = 5.558, p = .016, the covariate hierarchical complexity, *Wald* $\chi^2(1)$ = 16.738, $p \leq .0001$, the group X hierarchical complexity interaction, *Wald* $\chi^2(2)$ = 14.78, p = .001, and the group X gender interaction, *Wald* $\chi^2(2)$ = 6.529, p = .038 were significantly related to tool making; but not age in months, *Wald* $\chi^2(1)$ = 0.017, p = .897 (see Figure 26). The overall model was significant compared to the intercept only model, $\chi^2(9)$ = 38.085, $p \leq 0001$ (See Appendix B Supplementary Material 4, Table 9, Model 1, for parameter estimates).

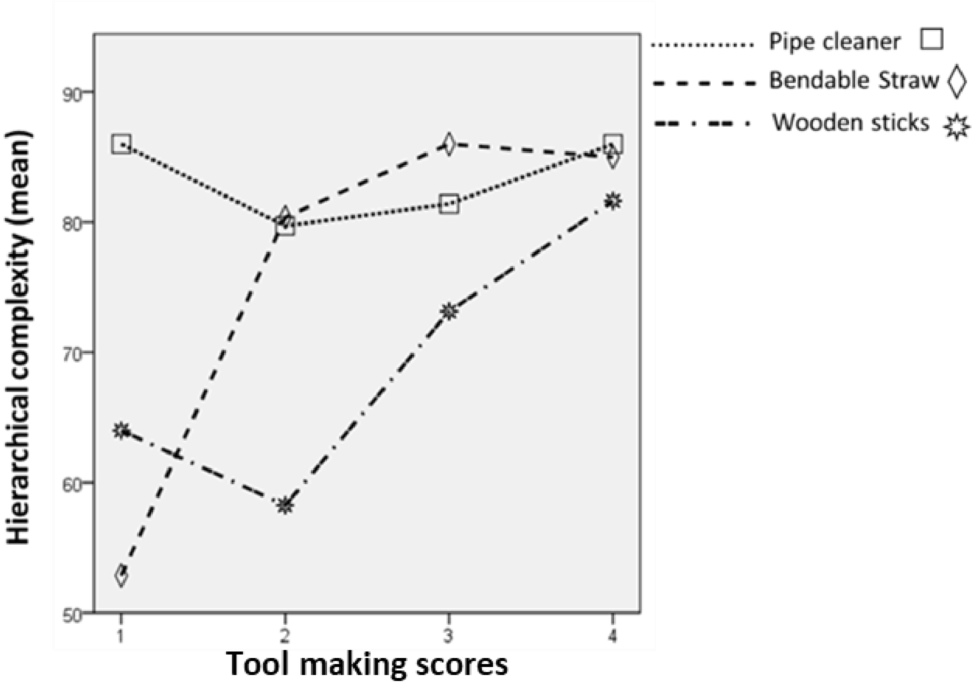


Figure 26: The relation between tool making scores and hierarchical complexity results. Square, star and tetragon symbols represent the mean hierarchical complexity results according to tool making scores.

Further assessments with Bonferroni corrected results (p ≤ .0167) indicated a significant positive Spearman correlation (one-tailed) between tool making scores and hierarchical complexity results in the WS group, r_s = .55, p = .002 , but not in the PC group, $r_s = .18$, $p = .21$ (see Figure 26). The correlation between tool making and hierarchical complexity was approaching significance in the BS group, $r_s =$ .38, $p = .029$; however, considering the medium effect size, the result was evaluated as if it was significant (see Figure 26).

Table 4: Kolmogorov-Smirnov (K-S) test results of the dependent variable (normality test) and descriptive statistics of both dependent and independent variables of each factor

		Tool making scores (dependent variable)					Hierarchical structuring task: complexity (covariate)			Divergent thinking (covariate, only in the WS group)		
		K-S test results			Descriptive statistics		Descriptive statistics			Descriptive statistics		
		D	*df*	*P*	*M*	*SE*	*Range*	*M*	*SE*	*Range*	*M*	*SE*
Group (factor)	Pipe Cleaner	.26	23	.0003	2.78	0.17	42 – 202	87.18	5.95	-	-	-
	Bendable Straw	.258	25	.0002	3.12	0.19	24 – 122	74.28	4.58	-	-	-
	Wooden Sticks	.19	27	.014	2.37	0.21	34 – 86	75.56	3.56	1 – 9	5.08	0.37
Gender (factor)	Boys	.211	43	.00005	2.98	0.14	34 – 202	82.51	3.82	-	-	-
	Girls	.216	31	.001	2.02	0.18	24 – 86	73.13	3.62	-	-	-

A GLM with a multinomial (ordinal) distribution and complementary log-log link function was calculated to predict tool making scores in the WS group with the factor gender, and the covariates hierarchical complexity and divergent thinking results. Bonferroni corrected significance results were used ($p \leq .0167$). Gender, *Wald* $\chi^2(1) = 7.754$, $p \leq .005$, hierarchical complexity, *Wald* $\chi^2(1) = 15.920$, $p \leq .0001$, and divergent thinking, *Wald* $\chi^2(1) = 11.870$, $p \leq .001$, were significant in predicting tool making scores (Figure 27), which makes the model significant compared to the intercept only model, $\chi^2(3) = 29.008$, $p \leq .0001$ (See Appendix B Supplementary Material 4, Table 9, Model 2 for parameter estimates).

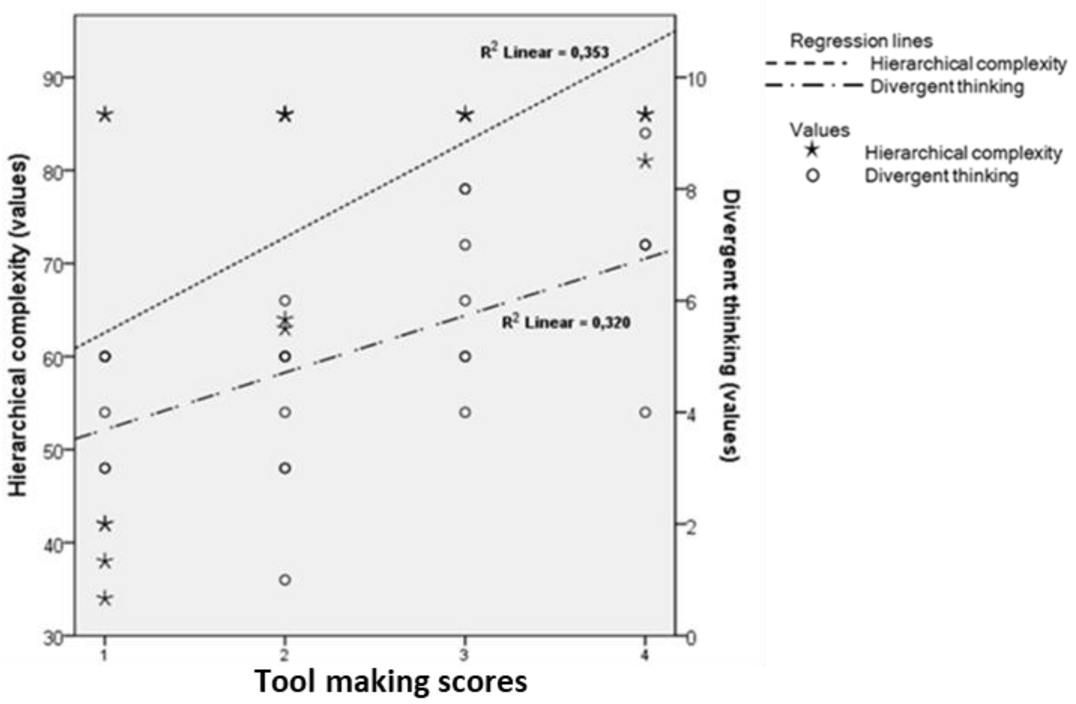


Figure 27: The relation between tool making scores and covariates in the oden stick group.

4.5. General discussion

The aim of the study was to determine the effect of perception-action related, representational, and creative factors on success in tool making in 5-to-6-year-old children. Results indicated that while adults' select the most salient of affordance tool (the pipe cleaner) for the hook task and solved the task with that tool, children were more successful making tools with the most familiar tool, the soda straw. It was shown that hierarchical complexity was a significant predictor of children's tool making scores in the wooden stick and bendable straw group, and divergent thinking results predicted tool making success in wooden sticks group. In parallel with the literature, we demonstrated that tool innovation (phase 1 tool making) was very difficult for preschool children. Tool innovation was not facilitated by the perceptual-motor properties of the tools. However, children could utilize social information at most if a very novel tool is used, e.g. pipe cleaner, and they could make a tool in the earlier phases with the bendable straw.

4.5.1. Adults' tool innovation and tool evaluation

In Study 1, adults were able to change the shape of the tool appropriately to the task before inserting it into the tube. Adults firstly selected the most salient tool in terms of affordance, and they used this tool to solve the task. However, they evaluated the pipe cleaner as the least familiar tool. Although adults evaluated the beddable soda straw as the most familiar, they often used the pipe cleaner or the wooden sticks to solve the hook task. These results are expected since adults can mentally rotate and manipulate images accurately according to the goal (Kosslyn, 2005) both with familiar and unfamiliar objects and images (Wexler, Kosslyn & Berthoz, 1998). Adults can easily perceive the affordances of a tool and predict its final structure, as in making stone tools (Nonaka, Bril & Rein, 2010), or they can use a tool in various alternative ways (Osiurak, 2010). Even though familiar tools are processed faster (Vingerhoets, 2008), adults can go beyond perceptual similarities and focus on the complex affordance relations and understand the technical requirements of the task in advance (Osiurak, 2010; Kalagher, 2015).

4.5.2. Tool making in children

Result of the Study 2 showed that preschool children have great difficulty in tool innovation in all groups, but their tool making can be facilitated by the interwoven interaction between social learning, perceptual-motor properties of the tool, and the representational abilities of the children. Children were better at tool making when using a highly familiar tool for the task, such as the bendable soda straw, compared to other tools, – even though it was not the one with the most salient affordance – as evaluated by the adults. Since children have perception-action knowledge of the relation between a straw and a bottle, their tool making might be facilitated by the perceptual-motor system in this case, allowing them to make the tool in the earlier phases of the task. The children in the wooden sticks group found the task most difficult. The affordance of the wooden sticks might not be salient for children for a couple of reasons. First of all, one reason for this may lie in the necessity of integrating more information while maintaining attention on the various parts of the tool (two sticks, holes), which might appear perceptually more complex. Note that the number of tools was kept the same among the groups. Nevertheless, the long rigid stick might have seemed sufficient to solve the task and thus, hindered the consideration of the crucial function of the small stick. For example, in the study of Nielsen, Tomaselli, Mushin, and Whiten (2014) children preferred more rigid tools, such as aluminum or wooden sticks, compared to flexible tools in an attempt to solve the hook task similar to the presented study. Secondly, when compared to the other tools, the bending (reshaping) action for the pipe cleaner and the straw might be easier than the combining (adding) action for the wooden sticks. Phylogenetic investigations show that a combining action is cognitively more demanding, as it is a type of composite tool making compared to manipulating, e.g., bending a single tool (Wadley, 2010; Oswalt, 1976; McGrew, 1987). In an unpublished study of Cutting, Beck and Apperly (in Cutting, 2013), with the same experimental design as in the current study, more children made a functional tool in the first two phases with reshaping the pipe cleaner compared to adding wooden sticks. Their results showed that 25 % of the 4-to-7-year-old children could make a functional tool in the first two phases, if children needed to add wooden sticks, while 51 % of them could do so, if they needed to reshape (bend or unbend) the pipe cleaner in the hook task.

4.5.2.1. Hierarchical structuring and tool making

The hierarchical complexity results were in parallel with previous developmental studies (Greenfield, 1991; Gönül, Takmaz, Hohenberger, & Corballis, 2018). As Greenfield (1991) states, the ability to make hierarchically complex structures is a matter of cognitive maturation. Considering the positive relation between the hierarchical complexity and the tool making scores, both abilities seem to be tapping into the development of technical understanding (Osiurak et al., 2016). It is most likely that being able to make a unified part-whole representation, as in making hierarchical structures (Greenfield & Schneider, 1978), in the process of imitation (Piaget, 1951) or during new knowledge construction (Mounoud, 1996), is also critical for tool making and its evolution (Gibson, 1993; Moore, 2010; Greenfield, 1991).

Results indicated a significant relation between the outcomes of hierarchical complexity and tool making only in the bendable straw and wooden sticks groups, but not in the pipe cleaner group. One reason might be that the pipe cleaner is a novel tool for Turkish children. This might prevent their hierarchical structuring abilities to facilitate solving the task. Instead, they may rely more on social learning and profit from being shown the ready-made tool or the making of the tool. For children in the bendable straw group, it can be claimed that if they could not come up with the solution already in the first phase, due to functional fixedness, social interaction might have helped them in concert with high hierarchical structuring abilities. Familiarity might sometimes be an inhibitory factor for novel problem solving (Hanus, Mendes, Tennie, & Call, 2011; Adamson, 1952). Note that in the bendable straw group, the (bending) action was familiar to children, as well as the relation between the straw and some receptacle. However, the resulting shape had a different functionality in the original use for drinking as compared to the novel use as a hook. Children may thus have had to overcome their functional fixedness – with the help of their hierarchical structuring abilities. For children in the WS condition, social interaction helped if they could not innovate the tool in the first phase. Seeing the ready-made tool was sufficient for children with high hierarchical structuring abilities indicating that these abilities helped them infer how to make an appropriate tool and utilize it in the task. Without hierarchical structuring abilities, this crucial step in the resolution of the task could not be achieved, though.

The crucial role of forming hierarchical representations in tool making has been emphasized in both ontogeny and phylogeny (see Elias, 2012; Hoffecker, 2012; Greenfield, 1991). For instance, in a development study, hierarchical complexity was positively related to tool making with the pipe cleaner as a tool in especially 3-to-4-year-old children (Gönül, Takmaz, Hohenberger, & Corballis, 2018). In this study, we also show that the complexity of hierarchical structuring was positively related to tool making if wooden sticks or bendable straw is used, but not pipe cleaner, in 5-to-7-year-old children. These contradictory results for the pipe cleaner might be explained by age ranges and different experimental designs between two studies. Although children after the age of 5 have difficulty in tool innovation, they are competent in social learning for the use of novel tools (Beck et al., 2011). Beyond that there were no ready-made tool demonstration phase in the study of (Gönül, Takmaz, Hohenberger, & Corballis, 2018).

4.5.2.2. Divergent thinking and making tools with wooden sticks

Beyond hierarchical complexity, the results of divergent thinking were significant in predicting success in tool making scores in the wooden sticks group, which may demonstrate a second level of recursion where hierarchically embedded knowledge is used for different imaginative contexts in tool making (Hoffecker, 2007, 2012). However, as the data and the literature suggest, although these abilities might share a common domain-general hierarchical representation capacity, the results of hierarchical structuring and divergent thinking can be different at the action level. In wooden sticks group, divergent thinking and hierarchical complexity were not correlated; yet, both of these factors facilitated tool making. On the other hand, children's divergent thinking scores (ideational flexibility) were higher with the pipe cleaner (the unfamiliar tool) than the pencil (the familiar tool). These results would help in the understanding of the effect of familiarity and novelty on creativity and innovation in terms of functional fixedness. In the domain of tool making, even though 5-to-7-year-old children think more divergently with pipe cleaner, they have difficulty in tool making with this very novel tool and rely on social information. Nevertheless, although divergent thinking is limited with a familiar tool (pencil), familiarity can also facilitate solving the hook task if the tool triggers perceptual-motor repertoire, e.g. via the bottle-straw relation. Moreover, hierarchical complexity and social information help to overcome functional fixedness in tool making, because children may not be cognitively ready to read the salient features of affordances to solve tool making problems as adults do. While the results from the current study indicate a relation between the tool making and divergent thinking, Beck et al. (2016) did not find a connection between divergent thinking and spontaneous tool innovation (Phase 1 of the current study) with a pipe cleaner. These contradicting results might be explained in terms of the types of the tool used in the current study or the difference between spontaneous tool innovation and the process of tool making through social interaction in which perception- and action-related information on the tool is accumulated. Furthermore, in the current study's divergent thinking task, the children were also allowed to touch the tools and explore them during naming their diverse functions, which might be ecologically more valid than showing photos.

4.5.2.3. The effect of gender

This study also found a gender effect with boys outperforming girls. Nevertheless, the interaction between gender and group were significantly predictive of the results of tool making, suggesting that the familiarity-novelty dimension might play a role in that effect. Tool making scores of girls and boys were very similar if only the pipe cleaner was considered, which is compatible with previous findings (e.g., Cutting et al., 2011, 2014; Chappell et al., 2013); however, boys outperformed girls, if soda straw or wooden sticks were used. We suggest that future studies should consider gender as a variable in relation to familiarity of tools.

4.5.2.4. Tool innovation

Although we did not specifically focus on tool innovation (Phase 1), 5-to-7-year-old children's immaturity in spontaneous tool innovation is very clear. Considering their inexperience, without prior social and perceptual-motor information about the end-state tool, tool innovation might not be possible in preschool children (see, Legare & Nielsen, 2015); however, children still need to combine previous perceptual-motor information within the task. This might make tool innovation cognitively more demanding compared to tool making after observing immediate modifications (e.g., ready-made tool demonstration or tool making action demonstration). In the hook task, children can select a functional tool– a hooked pipe cleaner (see, Beck et al., 2011), and in some rare cases they talk about or make gestures regarding a functional solution (e.g. saying ''a hooked cane would work''), or they draw a hook shape in the air with their fingers and say ''something like that would work'' even though they are not asked to do so (Gönül, Takmaz, Hohenberger, & Corballis, 2018). Although children might represent and simulate a functional solution for the presented hook task, they may not be ready for converting these simulations or mental manipulations into actions, in other words, for manipulating a novel tool spontaneously to solve a problem. Tool innovation might require two crucial skills: simulation and creative abilities, and controlled tool making. While 5-to-7-year-old children can be good at spontaneous creativity (e.g. divergent thinking in this study) and mental simulations/manipulations (Brandimonte, Hitch & Bishop, 1992), controling information hierarchically and implementing representations into actions might be challenging for preschool children without social learning. Stout et al. (2000) show that tool making activates areas in the brain responsible for spatial cognition, motor and multimodal processing, and visual associations (Stout, et al., 2000). We speculate that children's controlled mental manipulations precede controlled physical manipulations during innovative problem solving, which should be explored in the future.

In conclusion, in this developmental study we investigated the role of perceptual-motor aspects of tools (their familiarity and salience of affordance) and representational abilities (hierarchical structuring) and creative processes (divergent thinking) in the overall process of tool making. Results of the study show how 5-to-7-year-old children employ these aspects and abilities according to the type of tools. Children are better at tool making if the tool-task relation is familiar to them (perceptual-motor knowledge) as in the case of utilizing bendable straw. If the tool is perceptually more complex, rigid, and requires a combining action, as in the case of wooden sticks, they use representational resources (hierarchical structuring). However, if the tool is unfamiliar, such as the pipe cleaner, their representational abilities cannot play out. In this case, children depend on the social information. All children may profit from demonstration of the ready-made tool and the tool making during social interaction. Moreover, divergent thinking predicted children's performance in tool making with the wooden sticks, indicating a critical role of creativity in tool innovation (Carr, Kendal, & Flynn, 2016) and tool making (Mithen, 2005). Finally, we claim that children's difficulty in spontaneous tool innovation might be the result of their not being able to implement their actions according to their mental manipulations, which requires both spontaneous creativity and simulation capacity, and multimodal processing and hierarchical action control over physical manipulations.

CHAPTER 5

STUDY 3: JOINT AND INDIVIDUAL TOOL MAKING IN PRESCHOOLERS: FROM SOCIAL TO COGNITIVE PROCESSES[6]

5.1. Abstract

Tool innovation and creation have been proposed as key forces in driving the complexity of human material culture. The phylogeny as well as ontogeny of tool-related behaviors hinges on social, representational, and creative factors. In this study, we test the associations between these factors in development across two distinct cultures. Results of Study 1 with 5-to-6-year-old Turkish children in dyadic or individual settings show that tool making is facilitated by social interaction (peer dyadic interaction), hierarchical representation (hierarchical complexity), and creative abilities (divergent thinking). Results of a second explorative study comparing the Turkish data with a sample of 5-to-7-year olds in New Zealand suggest that tool innovation might be affected by culture, and that the role of cognitive and creative factors diminish through social interaction in tool making.

Keywords: Tool making, tool innovation, dyadic interaction, hierarchical representation, divergent thinking, culture.

5.2. Introduction

Tools are both the result and source of complex human material culture, and humans are known to be flexible toolmakers and tool users (Vaesen, 2012). The

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[6] This study, largely in its current form, is under revision as the paper:

Gönül, G., Hohenberher, A., Corballis, M., & Henderson, A. (under revision). Joint and individual tool making in preschoolers: from social to cognitive processes.

question remains as to how *H*. sapiens became more creative and flexible in tool making technology phylogenetically as compared to other animals and their ancestors, and how this ability develops ontogenetically. In this paper we investigate the social-cognitive development of tool making and possible representational and creative underlying this process with two studies. We also compare the empirical results with the phylogeny literature of tool-related behaviors.

5.2.1. Development of tool-related Behaviors

Human cognition is the outcome of its evolutionary history (phylogeny) and its development (ontogeny) (Langer, 1998). While there are many studies on the phylogenetic origins of human tool-related behaviors (for a review see Vaesen, 2012) its development has been considered less in the literature (Keen, 2011). Social and cognitive factors might work in tandem through the development of tool use (Deák, 2014). Even in the first year of their lives, infants demonstrate the ability to use everyday tools such as spoons (Connolly & Dalgeish, 1989) or crooks and sticks (Bates, Carlson-Luden & Bretherton, 1980), and they utilize social cues to use tools (Sage, & Baldwin, 2011). Their action planning with tools progressively improves in the second year (Rat-Fischer, O'Regan & Fagard, 2012). Brown (1990) shows that 2- to 4-year-old children can easily select functional tools to fetch a target. Between 5 and 7 years of age, children can define the function of a tool; and understand their goal-orientation and the intended use of tools (Defeyter & German, 2003). Regardless of the fact that children are good tool users, they are not proficient at making novel tools, i.e., spontaneous tool innovation.

According to Chappell et al. (2014) tool making has two main phases: *tool innovation* in which a functional tool is created individually to solve a problem, and *tool manufacture* in which the innovated tool is constructed by observing others via social learning (Chappell et al., 2014). In the *hook task*, modelled after a task used to test the cognitive abilities of New Caledonian crows by Weir, Chappell and Kacelnik (2002), children were required to make a hook from a straight pipe cleaner in order to get a bucket with a sticker out of a long vertical tube (Cutting, Apperly, & Beck, 2011; Beck et al., 2011; Beck et al., 2016; Nielsen et al., 2014). Results of these studies show that innovating a tool spontaneously to solve the hook task is difficult for children below the age of seven or eight. Children as young as 4 years can select the functional tool over non-functional ones (Beck et al., 2011), however they can rarely make a functional tool without a brief demonstration of the ready-made tool or demonstration of the tool-making action by an adult (Cutting, Apperly, & Beck, 2011; Chappell et al., 2013; Cutting et al., 2014). Some 3-to-4-year-old children still have difficulty in solving the hook task even after the social demonstration of the tool-making action (Gönül, Takmaz, Hohenberger, & Corballis, 2018), but after the age of 4, some children can make a tool after a brief demonstration of the ready-made target tool by an adult (Cutting et al., 2014). In other words, tool manufacture is relatively easy for 5-to-7-year old children. The seemingly gradual development of tool making has led researchers to examine the cognitive and social abilities/foundations that contribute to the development of tool making. We claim that peer interaction, hierarchical structuring and divergent thinking might be crucial for tool making in 5-to-7-year-old children.

5.2.2. Technical cognition, creativity and tool making: hierarchical construction and divergent thinking

The concept of *hierarchical construction of sequential behaviors* takes its roots from Lashley (1951), who calls it the syntax of action. Greenfield (1991) claims that the expansion of prefrontal cortex during evolution provided the basis for the mastery of *hierarchically complex manual combinations*, which in turn might have provided the basis for the evolution of tool-related behaviors and technical understanding. At the age of 3, children can combine their actions in a hierarchical way (Greenfield, Nelson, and Saltzman, 1972). Please see Appendix C Supplementary Material 1 ('examples for hierarchical action') for some examples for hierarchical action. After the age of 4, children become competent not only in making complex action sequences for combining objects, but also in spontaneously constructing embedded shapes, such as building a house with blocks (Reifel & Greenfield, 1983), building three-dimensional shapes (Beagles-Ross & Greenfield, 1979), or copying the shape of a hierarchical tree-like figure with straws (Greenfield and Schneider, 1977). The hierarchical complexity of shapes increases especially after the age of 5-to-6 (Greenfield and Schneider, 1977).

Hierarchical structuring and representation have also been proposed to be crucial for social learning (Byrne & Russon, 1998). In a series of studies, it has been shown that demonstrating the required tool use actions hierarchically in a social setting facilitates pre-school children's complex tool use understanding (Whiten, Flynn, Brown & Lee, 2006; Flynn & Whiten, 2008b). Many researchers have agreed upon the idea that hierarchical organization of information and action is crucial for tool making or complex tool use (Stout, 2011). However, is hierarchical organization of action and information enough for making a novel tool? Although hierarchical organization has a critical role, it is not useful if it is not transformed and used in different ways, which is the point "where creativity and innovation come in" (Elias, 2012, p.4). The phenomenon underlying the production of unlimited units or combinations from the elements of hierarchically structured representations is called recursion, and recursion might be the base of human creative and innovative culture (Corballis, 2014; Hoffecker, 2007).

The capacity of recursion can be seen in imaginative and divergent thought where an object is used beyond its perceptual and contextual boundaries (Callahan, 2013). Thus, divergent thinking (as an indicator of creative thinking) might be related to novel tool making, as both of them require going beyond perceptual and contextual boundaries. In their theoretical framework, Carr, Kendal and Flynn (2016) include divergent thinking as one of the main components in tool innovation. However, Beck et al. (2016) did not find any relation between spontaneous tool innovation and divergent thinking. Yet, if understood as a broader process comprised of various phases and social interaction, tool making might benefit from divergent and creative thinking (Mithen, 1998).

5.2.3. Social Cognition, Dyadic Interaction and Tools

Beyond these representational and creative factors which can be called technical understanding and creative thinking (Mithen, 2003), it is also known that children's complex tool use might be facilitated by seeing modifications being made on the tool, through observing an adult manipulating the tool (Carr, Kendal & Flynn, 2015). Studies of Cutting and colleagues steadfastly demonstrate that showing a ready-made functional tool or how to manipulate the tool (e.g. pipe cleaner) in regard to reaching the goal facilitates tool making (Cutting, Apperly, & Beck, 2011; Beck et al., 2011).

However, children not only learn from adults, they also learn tool-related behaviors from their peers (Flynn & Whiten, 2008a). Using the social diffusion method Flynn and Whitten (2008a) and Hopper et al. (2010) show the readiness of preschoolers to socially learn from their peers in tool-related behaviors. Furthermore, dyadic interaction may enhance individual problem solving capacities (Tomasello et al., 2005; Sebanz, Bekkering, & Knoblich, 2006). Five-year-old preschool dyads outperform independent preschool children in an object construction task, e.g. replicating a Lego model (Azmitia, 1988). Not only object construction, but also problem solving is facilitated by dyadic interaction. Cooper (1980) shows that 3-to-5-year-old dyads (same gender, same age and close friend pairs) are better and more efficient in a problem solving task requiring understanding physical properties.

Both individual differences and social learning play an indispensable roles in cumulative cultural traits (Mesoudi et al., 2016), as apparent in the emergence and spread of innovative behaviors (Rawlings, Flynn, & Kendal, 2016). Learning how to make a tool may appear in the process of the interaction with the tool(s) in the task context and the social setting. Therefore, in the present study, we evaluated tool making as a process in which the solution might appear through individual-dyadic (tool innovation) or social learning (tool manufacture). Without any social information the number of children who can spontaneously solve tool innovation problems is surprisingly low before the age of 7-8 (Cutting et al., 2011).

5.2.4. Aims and predictions of the study

The two studies reported here aim to reveal social, representational, and creative factors underlying preschoolers' tool making ability. We used Beck et al.'s (2011) bending task (hook task), but with a different tool (two wooden sticks, see 'Materials' section and Figure 28). Individual children and dyads may solve the task in one of three experimental phases where the adult experimenter provided information about the tool in the second and third phases.

We predict that (a) being in dyadic interaction, (b) competence in hierarchically complexity, (c), and divergent thinking enhance tool making of 5-to-6-year-old children. In the second explorative study, we investigate possible cultural factors underlying tool making in dyadic interaction. Note that one of the groups in this study (individual group) has been used in one of our previous studies with a different theoretical motivation (see, Chapter 4). While the effect of hierarchical structuring and/or divergent thinking on tool making has been shown in earlier studies with younger age groups or with different tools, in this study, we aim to investigate the role of these abilities in the process of tool making in a different social setting, i.e., peer interaction.

Different types of innovations might be affected by cultural dynamics (Muthukrishna & Henrich, 2016), such that cultural context and norms might affect dyadic interaction (Tomasello & Rakozy, 2003). Thus, in our explorative second study, we questioned whether dyads from different cultures, namely Turkey and New Zealand, would solve the innovation task differently. Please see Appendix C Supplementary Material 2 ('culture and the second study') for further information.

5.3. Experiment 4

5.3.1. Method

5.3.1.1. Participants and experimental groups

58 children, 5-to-6-years of age, participated in the study. There were two groups: 27 children in the individual group (10 girls, M_{age} = 68 months 3 weeks, *Range* = 60-81 months), 28 children (14 dyads) in the joint group (16 girls, M_{age} = 69 months 3 weeks, *Range* = 62-77 months). Data from the individual group has also been reported in an unpublished study of us (see Chapter 4) as wooden sticks group. Peers in dyads had the same gender, and the maximum age difference between peers was 1.5 years. The sample size of the joint group was compatible with other dyadic interaction studies in collaborative problem solving with children (e.g., Warneken, Stenwender, Hamann, & Tomasello, 2014). The ethnical composition of both groups was predominantly Turkish. All children were native speakers of Turkish and they were attending a kindergarten in Muğla, Turkey. Dyads were selected according to the kindergarten teacher's opinion about their friendship and communicative relations. Only same gender peers who were close friends and playing with each other more often than with others in the same class were selected as dyads.

5.3.1.2. Materials

One criterion – hook task – and two predictor tasks – hierarchical structuring and divergent thinking – were used in the study.

5.3.1.2.1. HOOK TASK

The materials used in the hook task were: a long wooden stick (length = 27.5 cm, diameter = 1.5 cm) with two holes (diameter = 0.7 cm) that were 1.5 cm away from the end points and a short stick (length = 3.5 cm, diameter = 0.5) fitting into the holes of the long stick. A transparent plastic tube [height = 22 cm, width of opening = 6 cm (covered with a 6 cm diameter carton circle with a 4 cm internal opening)] was vertically attached to a square wooden board (length = 30 cm), and a small bucket (depth = 1 cm, diameter = 3.2 cm, length of the handle = 9.5 cm) were used. A small sticker was put into the bucket as incentive (Figure 28).

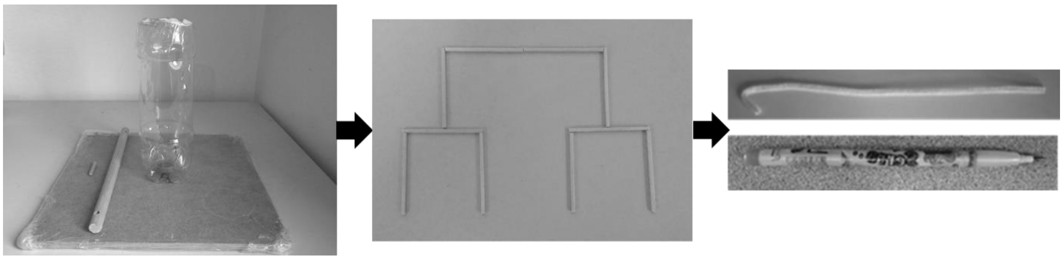

Figure 28: Materials used in the tasks. Hook task, hierarchical structuring task, and divergent thinking task materials from left to right, respectively. Arrows indicate the experimental sequence.

5.3.1.2.2. HIERARCHICAL STRUCTURING TASK

A simplified version of Greenfield and Schneider's (1977) hierarchical tree structure task was used. The materials used for the hierarchical structuring task were ten short wooden sticks (length=4 cm,) and an A4 size photo of the end-state tree shape to be made by the sticks (Figure 28).

5.3.1.2.3. DIVERGENT THINKING TASK

An adapted version of the Alternative Uses Divergent Thinking Task (Guilford et al., 1978) was used. One rigid familiar object (20 cm pencil) and one flexible unfamiliar object (30 cm pipe cleaner) were used (Figure 28).

5.3.1.3. Procedure

All the children were tested in a quiet room in their kindergarten. The materials that were used for the experiment were presented on a table. The experimenter and the child/dyad sat across the table. The whole sessions were video-recorded.

5.3.1.3.1. HOOK TASK

The experimental procedure of the hook task included one warm-up and three tool-making phases. A similar procedure was used by Cutting, Apperly, Chappell, and Beck (2014) [also see, Cutting, Beck and Apperly (in Cutting, 2013) for the wooden sticks task].

5.3.1.3.1.1. Warm-up (20-30 seconds)

The children were allowed to play with the tools (one short and one long stick per child). They were given prompts to explore the materials: ''e.g., explore the tools with your hands, which one is shorter?, which tool is longer?''. The experimenter then retrieved the tools.

5.3.1.3.1.2. Phase 1 (1 min)

The experimenter then introduced the bottle with the sticker in it and told children that, if they could successfully retrieve the sticker, they may keep it. The tools (one short and one long stick - Figure 28) were brought out by the experimenter. The experimenter told the participants that they could use these tools to get the sticker. In order to solve the task, children must realize that they need to combine the short and the long stick to form a hook in order to get the bucket inside the bottle out.

5.3.1.3.1.3. Phase 2 (30 sec)

If they were unable to solve the task, an already combined 'hook' was demonstrated and they were asked again to solve the task (ready-made tool demonstration phase).

5.3.1.3.1.4. Phase 3 (30 sec)

If, still, they were unable to solve the task, the experimenter showed them how to combine the two sticks and asked the children to solve the task (tool-making action demonstration phase). If children still did not complete the task after this phase, the task was ended.

After the child/dyad had completed the hook task, the predictor tasks were conducted individually for each child: first, the *hierarchical structure task* and then the *divergent thinking task*. While the experimenter was completing the tasks with one child, the other child waited in his/her class.

5.3.1.3.1. HIERARCHICAL STRUCTURING TASK

In this task, the experimenter presented the child with a photo with a tree-like shape made by small wooden sticks. While the photo remained on the table, the child was asked to reproduce the same shape on the surface of the table with 10 pieces of sticks that had the same size as on the photo. The experimenter waited until the child indicated that she was finished with the task.

5.3.1.3.2. DIVERGENT THINKING TASK

For the divergent thinking task, one familiar object (pencil) and one unfamiliar object (pipe cleaner) were shown to the children for one minute each, in counterbalanced order. Children were asked: “Can you please tell me the things that you can do with this thing”, and further prompted by asking “what else?”, “how can you play with it differently?”, “what else can you do with it?.” Children were prompted after each response with saying: “yes, you can do … with it, what else?” After the tasks, children were accompanied to their classes.

5.3.1.4. Coding, data analysis, and data reduction

The experimenter (G.G.) from the recorded videos coded data. Another person who was not a part of the study coded %50 of the data for inter-rater reliability. Success of retrieving the bucket from the tube in each phase was coded for two reasons: 1) to allow for a comparison between our results and the literature and 2) to test for differences between groups at each phase. Various *chi-square* tests were used to calculate the difference in distribution of children/dyads in the various phases. Two-sided *Fisher's Exact Test* (*FET*) was used if there was any expected cell count less than five. However, as tool making could be a cumulative learning process based on exploration and social learning, we also coded tool making as an ordinal variable (tool making scores): a child or a dyad could obtain 4, 3, 2, or 1 points according to their success in Phase 1, Phase 2, Phase 3, or no success in any of the phases, respectively. Tool making scores were used in the main models (see below). Inter-reliability for the 50% of the dyads for their tool making success in phases was 100%.

A hierarchical complexity measure was calculated from the hierarchical structure task based on graph theory, as used by Greenfield and Schneider (1977) with a slight modification. A score of 1 was given for simple edges; 4 (2^2) for junctions of two edges, 9 (3^2) for junctions of three edges, and 27 (3^3) for junctions of two edges in the middle (the only modification in measurement to obtain a more precise complexity measure). Thus, the sum of scores gave us the hierarchical complexity score (See Figure 29).

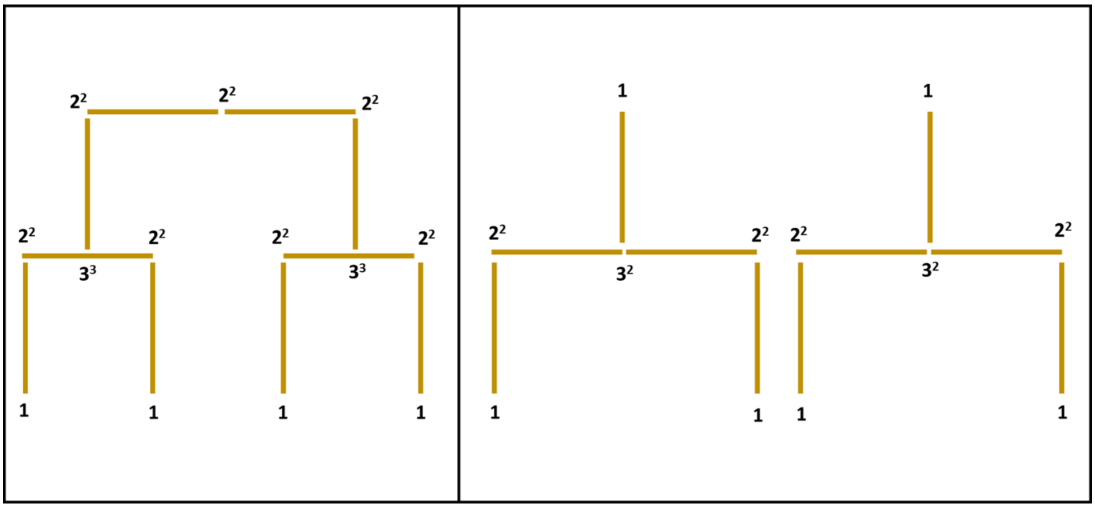

Figure 29: Schematic drawing of the two shapes of the hierarchical structuring task made by children and complexity scores for each node. The left one has the same structure with the target shape.

In the divergent thinking task, the total number of enumerated categories (types) of actions for two objects was counted, to give a measure of ideational flexibility. Tokens of the same category, e.g., 'writing, drawing, painting, coloring' were not counted. Two children (both in the individual group) did not have divergent thinking results (1 experimenter error, 1 would not speak due to excessive shyness) and thus, their results were excluded pair-wise or list-wise according to the test. For the joint group, the experimenter (G.G.) categorized counted responses based on the categories from our previous study (see Chapter 4). Inter-rater reliability was high between the two coders for the 50% of the participants in the joint group, *Cronbach's* α = .901.

In order to make data from individuals and dyads commensurable, data from dyads were combined into single scores. Thus, each dyad had one tool-making score. For the predictor task measures (hierarchical complexity and divergent thinking) the mean score for each dyad was used.

In this study, a Generalized Linear Model (GLM) is used to analyze the ordinal data of the tool making scores along with the predictor tasks. See Appendix C Supplementary Material 1 ('data analyses') for the detailed explanation on model construction and analyses.

5.3.2. Results and discussion

5.3.2.1. Tool making in phases

There was a significant difference between girls and boys (dyads or individuals) in phase 1, *FET*, p = .027, ϕ = -.37. Boys were better in tool innovation than girls. There was no gender difference in phase 2, $\chi^2(1) = 0.024$, p = .877, and phase 3, *FET*, p = .17. Results indicated that success in phase 1 was not significantly different between individual and joint groups, *FET* (two-sided), p = .408. However, children in the joint group were significantly more successful in phase 2 than the individual group, $\chi^2(1) = 4.61$, p = .032, ϕ = .36. Success in phase 3 was not significantly different between individual and joint groups, *FET* (two-sided), p = .603. Overall, there were no significant difference between groups in terms of success (in any phase), *FET* (two-sided), p = .227 (see Table 5).

Table 5: Number (percentage) of Successful and Unsuccessful Individuals or Dyads across Phase and Group

	Successful			No success
	Phase 1	Phase 2	Phase 3	
Individual	5 (18%)	7 (26%)	8 (30%)	7 (26%)

Joint	1 (7%)	9 (64%)	3 (22%)	1 (7%)

These results indicated that tool innovation (phase 1 tool making success) is difficult for young children (Cutting et al., 2011). However, tool making after the ready-made tool demonstration was easier. While only a quarter of the children in the individual group could make a functional tool in phase 2, after demonstration of a functional tool, more than half of the dyads were able to create a tool in the same phase. We may infer from this result that dyadic interaction facilitated children's tool making performance in the second phase. Thus, children's joint attention with each other may have created perceptual common ground for joint action (Sebanz, Bekkering, & Knoblich, 2006). Even if just one child tried to solve the task in the first phase, her companion might have realized the intention of her peer, creating a shared representation of events and objects. The shared representation and intention understanding might facilitate understanding the intention of the experimenter by demonstrating the functional tool. Thus, the dyad could combine that information with the task goal more easily.

5.3.2.2. Predictor tasks and tool making as a process.

As mentioned in 'Coding, data analysis, and data reduction' section, we also consider tool making as a process rather than a non-or-one phase. Accordingly, the tool-making scores were used as ordinal scores in the subsequent analysis. Furthermore, the process treatment might also be better suited for the small sample size in phases. A child or a dyad could obtain descending tool-making scores (4, 3, 2, or 1) according to their success in Phase 1, Phase 2, Phase 3, or no success in any of the phases, respectively. Results and discussion of the preparatory analyses are given in Appendix C Supplementary Material 2 ('Study 1: preparatory results and discussion').

Predictors of tool-making scores were selected based on the hypothesis of the study and preparatory results (e.g., gender effect). Consequentially, group (individual or joint Turkish) and gender were included as factors, and hierarchical complexity and divergent thinking (pipe cleaner and pencil) as covariates.

An ordinal logistic regression with complementary-log-log link function with GLM was conducted to predict descending tool-making scores. The *Likelihood Ratio (LR) chi-square* result of the test of model effects showed that the factors group, *LR* $\chi^2(1) = 3.917$, $p = .048$, and gender, *LR* $\chi^2(1) = 8.136$, $p = .004$ (see Figure

30), the covariates hierarchical complexity, *LR* $\chi^2(1) = 19.586$, $p \leq .0001$, divergent thinking with the pipe cleaner, *LR* $\chi^2(1) = 6.103$, $p = .013$, and divergent thinking with the pencil, *LR* $\chi^2(1) = 6.212$, $p = .013$, were significantly predicting tool-making scores (see Figure 30 and Appendix C Supplementary Material 2 –Table 10– for descriptive statistics). The overall model was significant compared to intercept-only model, *LR* $\chi^2(5) = 34.986$, $p \leq .0001$. Boys got higher tool-making scores than girls, and tool-making scores were higher in dyadic interaction than in the individual setting. Covariate measures decreased with the descending tool-making scores (see Appendix C Supplementary Material 2 –Table 11– for parameter estimates).

Bonferroni corrected (with the alpha level of .025) one-tailed Spearman correlations were computed to clarify GLM results for both groups. Results showed that tool-making scores and hierarchical complexity were significantly correlated in the individual group, $r_s = .632$, $p = .0002$. Beyond that, tool-making scores were significantly correlated with divergent thinking with the pipe cleaner, $r_s = .511$, $p = .005$, but the correlation between tool-making scores and divergent with the pencil was approaching significance, $r_s = .39$, $p = .027$. In the joint group tool-making scores were not significantly correlated with the divergent thinking with the pipe cleaner, $r_s = .085$, $p = .387$, or with the pencil, $r_s = .292$, $p = .155$. However, there was a marginally significant correlation between tool-making scores and hierarchical complexity, $r_s = .475$, $p = .043$.

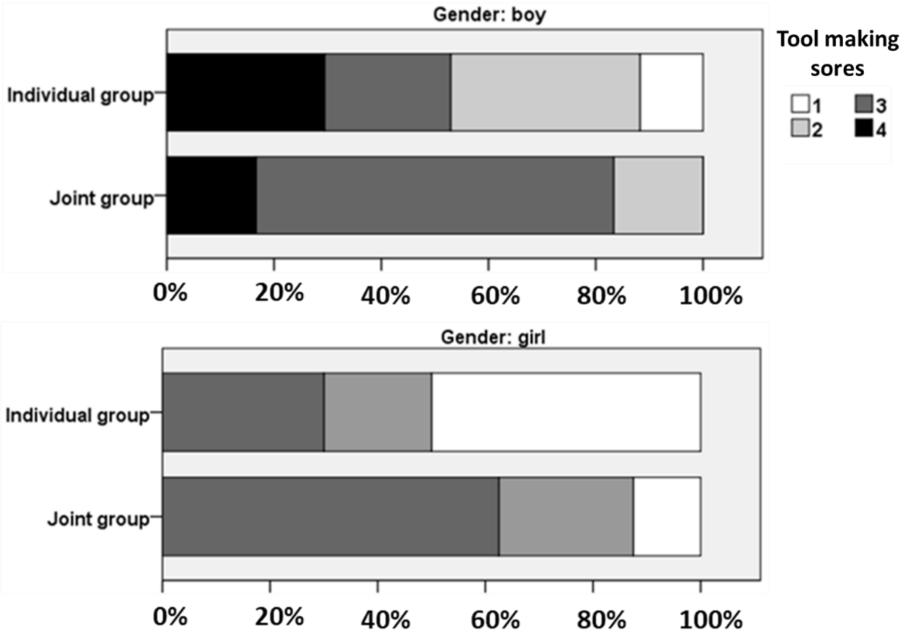

Figure 30: Tool-making scores (percentages) between individual and joint Turkish groups, according to boys and girls.

These results were consistent with evolutionary and developmental explanations which claim that the hierarchical structuring capacity of the mind was crucial for constructing tools (Greenfield, 1991; Stout, 2011) and that human tool-making capacity might have flourished with enhanced divergent thinking and creative capacity (Mithen, 1996; Carr, Kendal, & Flynn, 2016). Using the same hook task with a pipe cleaner as a tool, Beck et al.'s (2016) results showed that divergent thinking was not a significant predictor of spontaneous tool innovation in older children. However, we did not only investigate tool innovation (Phase 1), but also included the other phases as an ordinal variable into the model. On a broader phylogenetic scale, our divergent thinking results are compatible with claims on the co-evolution of symbolic thought and material culture (Mithen, 2003).

Although the hierarchical structuring ability manifests itself also in the joint group– though less strongly as compared with the individual group – divergent thinking did not. Social interaction might have rendered the influence of individual divergent thinking in the joint group superfluous since both partners' contributions in the joint group were as divergent as that of a single participant in the individual group. Taken together, social interaction in the joint group might have reduced reliance on individual conceptual/representative and creative resources, but fostered pooling and sharing of these resources. Observational results support the idea that in the joint group children indeed focused on the actions of their peers.

Although overall tool-making scores were higher in the joint group, the reason why joint interaction did not increase the tool innovation performance (in other words, phase 1 success) needs further clarification. The hook task itself does not require joint interaction; however, the presence of the other person might still increase tool-making performance in the later phases, as our results indicate. One reason might be language: partners in the joint task naturally communicate with each other about their ideas and actions. As is known from studies with adults, language may help in forming more abstract representations and foster rule-based behaviors (Tylén et al., 2016). Language might therefore facilitate problem solving as the partners would overtly and explicitly express their (divergent) thoughts. Another reason might be the conceptualization of the task as a joint action. Observational results suggest that dyads considered the task as a problem that ought to be solved together, e.g. they grabbed the long stick together, and shared the tools (one got the long and the other got the short stick). These observations raise the question of whether their conception of the situation as a dyadic one might have hindered children's tool innovation. One possibility is that cultural norms might affect children's approach to the task. Turkey is known as a "collectivist" culture (see, Oyserman et al., 2002) which may already be manifest in children's conception of, and behavior in, joint tasks. If for Turkish children solving the problem together was mandatory, they may not have dared to solve it individually – even though this might have resulted in better success in phase 1. Following up this line of reasoning and clarifying the possible role of cultural conceptions of joint action, we collected data from another joint group from a more western-oriented culture, New Zealand. Our aim with this second study is to compare the results of children stemming from those two different cultures – one collectivist (Turkish) and one individualistic (New Zealand). Note that the second study has explorative rather than experimental.

5.4. Experiment 5 (explorative)

In this exploratory study, the Joint Turkish group from the Experiment 5 was compared with another joint group from New Zealand.

5.4.1 Method

5.4.1.1. Participants

Data from 32 children (16 dyads) from New Zealand (10 girls, M_{age} = 70 months 1 week, *Range* = 61-78 months) were collected in the Early Learning Lab (ELLA) of the University of Auckland. As the primary school education starts at the age of 5 in New Zealand, all the New Zealand participants were attending school. Additional data from 6 New Zealand children (3 dyads) were not included in the final composition because of technical error (1 dyad, girls), having an age difference more than 1.5 years between peers (1 dyad, boys), not being competent in understanding English (1 dyad, boys). For this group, two children who were friends were invited for the session to the ELLA lab, together with their parents. Thus, to book participants in New Zealand, we contacted one parent and kindly asked them to invite a friend of his/her child (and the parent) to come to the lab session. The ethnical composition was predominantly New Zealand European (23 children) or New Zealand European mixed with other ethnic groups (6 children). The rest of the group was Asian (1 child), African Black (1 child), and Asian and Latin American mixture (1 child). All the children in the group were fluent native speakers of English, born and raised in New Zealand.

5.4.1.2. Materials and procedure

Materials and procedure were the same as those used for the joint group (Experiment 4).

5.4.1.3. Coding, data analysis, and data reduction

Coding and data analyses were the same as in Experiment 4 (except for the divergent thinking task). Divergent thinking results of the New Zealand group were firstly coded and categorized by the experimenter (G.G.) based on the categories from our previous study (see Chapter 4). Then a second person, who is competent in speaking and understanding English, and not a part of the study, categorized the responses (Cronbach's α = .90). All the incompatibilities were resolved through discussion. Divergent thinking results of one dyad in joint New Zealand group were excluded because of experimenter error.

5.4.2. Results and discussion

5.4.2.1. Tool making in phases

There were no gender difference in phase 1, *FET*, p = 0.99in phase 2, *FET*, p = 0.99, and phase 3, *FET*, p = 0.99. Results showed that the difference between Turkish and New Zealand children in phase 1 success was significant, *FET*, p = .039, with a medium effect size, ϕ = .413. While 44% of New Zealand children spontaneously innovated the tool in phase 1, only 7% of Turkish children did so. Phase 2 success results were not significantly different between groups, *FET*, p = .99. Phase 3 was also not significantly different between groups, *FET*, p = .99 (see Table 6).

Table 6: Number (percentage) of Successful and Unsuccessful Dyads across Phases in New Zealand Group

	Successful			No success
	Phase 1	Phase 2	Phase 3	
Joint New Zealand	7 (44%)	7 (44%)	2 (12%)	0 (0%)

Results demonstrated that the effect of gender was not significant anymore in the joint interaction. Significantly more children in the New Zealand joint group innovated a tool in the first phase than the Turkish children in the joint group. This difference may be explained in terms of a cross-cultural difference along the individualist/collectivist dimension. Children from New Zealand might have represented both of the tools (short and long stick) as things they could each use individually at the same time and thus, may not have viewed this task as a collaborative task. On the other hand, Turkish children, who come from a more collectivistic culture, might have viewed this as a collaborative task form the start. In this case, it could be argued that Turkish children represented each tool separately, e.g., each child could take one tool and leave the other tool to his/her partner, or they may take turns in order to use the most functional one, or they may use the long stick together. For example, two dyads in the Turkish group grasped the long stick together and tried to pull the bucket up together. A further reason may be a linguistic difference in understanding the pronoun "you" in the instruction for collaboration. While the English “you” is ambiguous between singular and plural, the Turkish “siz” is unambiguously plural in the joint context. Thus, Turkish children may have interpreted the request in terms of mandatory collaboration whereas NZ children may not have.

5.4.2.2. Predictors of tool-making scores

Predictors of tool-making scores were selected based on the hypothesis of the study and preparatory results (e.g., gender effect). Results and discussion of the preparatory analyses are given in Appendix C Supplementary Material 2 (‘Study 2: preparatory results and discussion’). An ordinal logistic regression with complementary-log-log link function with GLM was calculated. The factor group (joint Turkish or New Zealand), $LR\ \chi^2(1) = 0.149$, $p = .699$, was not significantly predicting tool-making scores. The *Likelihood ratio chi-square* result of the test of model effects showed that none of the covariates were significantly predicting tool-making scores: hierarchical complexity $LR\ \chi^2(1) = 3.807$, $p = .051$, divergent thinking with the pencil, $LR\ \chi^2(1) = 0.272$, $p = .602$, divergent thinking with the pipe cleaner, $LR\ \chi^2(1) = 1.508$, $p = .220$ (see Appendix C Supplementary Material 2 –Table 12– for descriptive statistics). The overall model was not significant compared to intercept-only model, $LR\ \chi^2(4) = 7.609$, $p = .107$.

Bonferroni corrected (with the alpha level of .025) one-tailed Spearman correlations were computed to clarify GLM results for the New Zealand group. Results showed that tool-making scores were not significantly correlated with hierarchical complexity, $r_s = .339$, $p = .10$, divergent thinking with the pencil, $r_s = .077$, $p = .392$, and divergent thinking with the pipe cleaner, $r_s = .093$, $p = .371$.

Although the effect of hierarchical complexity was still prominent, in the GLM model, it was not correlated with the tool-making scores in the New Zealand group. As explained in the Appendix C Supplementary Material 2, the New Zealand children got higher scores from hierarchical complexity, and most of them copied the exact shape, which might be the result of early schooling. More complex hierarchical complexity tasks should be used in the future studies to prevent ceiling effects.

5.5. General discussion

In this study, we aimed to identify the extent to which representational, creative and social interactive factors underlie children's tool making. In Experiment 1, we showed that representational and creative factors, namely hierarchical representation and divergent thinking, are critical for tool making mostly in an individual context. Peer interaction facilitated tool making in the second phase, namely after social learning. However, results of the explorative Experiment 5 indicate that there might be an effect of culture and early schooling on the results of divergent thinking and hierarchical structuring tasks, which impinge upon their tool-making results in joint interaction (see Appendix C Supplementary Material 2). Besides, our results showed that children had difficulty in tool innovation (Phase 1), which was compatible with Beck et al.'s (2011) results. Social interaction, namely demonstrating the tool and how to make it, facilitated tool making. Furthermore, we explored culture as another variable possibly affecting the process of tool making in peer interaction.

In Experiment 4, Phase 1 results indicate that tool innovation is hard for children in both individual and joint conditions. However, their developed social cognition may help children how to solve the hook task after the age of 5. This is suggested by the results of Phase 2 and Phase 3 in this study, e.g. if the ready-made tool was provided or the tool-making action was demonstrated by the adult experimenter. However, children in the joint group were more successful than individual children in Phase 2. This finding supports the idea that peer interaction facilitates problem-solving performance in tool making, especially in Phase 2. Perhaps the benefit of (verbal and motor) interaction needs some time to play out, such that no advantage is expected in the first phase but in later phases of the tool making process. The results of GLM analyses with the tool-making scores indicated that hierarchical structuring and divergent thinking were significant predictors of tool-making scores. These results were in parallel with some evolutionary and development explanations, arguing that humans' hierarchical and recursive thinking capacity was crucial for constructing tools (Greenfield, 1991; Stout, 2011). We also obtained evidence for some slight decrease in the predictive power of hierarchical representation and a significant decrease in the predictive power of divergent thinking in peer interaction as compared to individual tool making. These findings suggest that core cognitive functions such as hierarchical representations might not be shared between the partners in joint action, however, creative functions might be. In the joint tool-making task, children may focus on social cues while solving the task.

Results of the cross-culture study showed that there were more tool innovators in the New Zealand joint group than in the Turkish joint group. Though explorative, the second study also indicated some cultural differences that might affect dyadic interaction in tool making. Children raised in a collectivist culture such as Turkey may take a more collaborative perspective even though the task does not specifically require collaboration, whereas children raised in an individualist culture such as New Zealand may not feel compelled to act jointly to the same extent. Future research should clarify the effect of the instruction to act together considering language differences. Beyond that, divergent thinking results of individuals influenced tool-making scores differently between the two cultures in the present study. While divergent thinking with the pencil (a familiar and functionally fixed object) and tool-making scores were related to each other in the New Zealand joint group, they were not correlated in the Turkish joint group. We claimed that it might have based on early schooling. All the Turkish children in this study were attending kindergarten, which might have contributed their pretend play with familiar tools.

The present study has some limitations, which most of them related to the explorative nature of the second study. First, since the sample size of the second study is relatively small, further investigation is needed in order to clarify in particular the effect of cultural differences in different types of tool innovation problems during joint interaction. To the best of our knowledge, neither the effect of dyadic interaction on tool making nor the effect of culture on dyadic interaction in tool making has been systematically investigated hitherto. Results of this study may lead to more systematic research on the subject in the future. Second, there was no New Zealand individual group to which the results of the Turkish individual group could be compared. Yet, in another Western oriented culture (UK), results of the hook task with the same experimental procedure and nearly identical tools indicated very similar results to the individual Turkish group of our first study [see Cutting, Beck and Apperly (referred to in Cutting, 2013)]. See Appendix C Supplementary Material 3 for further discussions. Children of families who came to the lab at the Auckland University may have been more motivated to explore and solve problems as compared to the Turkish dyads who were tested in kindergarten. For example, in Sheridan et al.'s (2016) study, which was conducted in a museum – an extra-ordinary place – the percentage of child tool innovators was higher compared to previous studies conducted in ordinary places such as a kindergarten. Therefore, conducting an experiment with joint groups in a school in New Zealand could shed further insight on the nature of the results reported in our second experiment. The other point is that each dyad had one score from the hook task, and one score for each predictor tasks from which mean scores of the two peers was calculated. Alternatively, these tasks might also have been shared by the dyad, i.e., the hierarchical structuring task and the divergent thinking task might have been solved together. Yet more complex methods might be used in the future to analyze this type of data to find out which child contributed to the dependent variable (see, Guevara et al., 2017). Additionally, there were markedly fewer girls in the New Zealand group. Despite the attempts, families of girls were not eager to allow their children to be participated in a tool-making study. Although this was unintended, it is possible that the study description used in the emails that were sent to recruit families in New Zealand may have seemed gender-biased. Future studies might consider revising the study descriptions to encourage more females to participate in the study. However, parents' tendency in both cultures to allow their children to be participated in a tool-making study if they have boys show something that should be considered in the future studies, which could enhance understanding of the reasons underlying the gender differences found in the present study. Lastly, results of the tasks seems to suggest that there might be an effect of early schooling on the measures presented in this study. Future studies should consider this effect.

In conclusion, the two studies reported here provide evidence suggesting that tool making is facilitated by hierarchical complexity and divergent thinking in individual children. Moreover, tool making is facilitated by social interaction such that children profit from obtaining more and more clues about the solution such as seeing the ready-made tool or observing the tool making. We obtained further evidence that a peer might benefit from dyadic interaction in tool making such that the two partners may solve the task more easily. Taken together, children in dyadic interaction with the peer focus on social resources (demonstrations of the experimenter or their peers) during the hook task, which might affect the contribution of divergent thinking and hierarchical structuring. The results of our developmental study are largely consistent with the literature on the phylogeny of tool making, suggesting that both areas of research can inform each other.

CHAPTER 6

GENERAL DISCUSSION, FUTURE DIRECTIONS AND CONCLUSION

6.1. General discussion of studies

Overall, our results showed that children had difficulty in innovating a tool (Phase 1), which is consistent with those reported by Beck et al. (2011). Social interaction (adult-child), namely demonstrating the tool and how to make it, facilitated tool innovation. Inhibition latency significantly predicted tool making success especially in younger children (Experiment 1). Furthermore, hierarchical complexity and divergent thinking were found to be significant predictors of tool making process. These results are parallel with evolutionary and development explanations suggesting that the recursive and hierarchical thinking capacity of the mind is crucial for constructing tools (Greenfield, 1991; Stout, 2011). In Experiment 2, before inserting the tool into the tube, adults changed the shape of the tool in an appropriate way to achieve the goal. Adults can easily perceive the affordances of both tools and the tasks, and predict the future outcomes of the end-state structure of a tool (Osirurak, 2010); however, as shown in this study, children react in a different way. Understanding complex affordance relations may require making a comprehensive/whole representation of the tool for the target while considering the particular functions of the parts, which children begin to achieve from 5 to 7 years old and become increasingly better after this age (Mounoud, 1996). Thus, using a familiar tool might have activated previous information about the tool-task relation (e.g., straw-bottle) and facilitated a tool making process unlike pipe cleaner or sticks. Experiment 4 showed that the dyadic interaction facilitates the tool innovation in Phase 2. The children's collective attention may have created perceptual common ground for joint action (Sebanz, Bekkering & Knoblich, 2006). Even if just one child tried to solve the task in the first phase, her companion might have realized the intention of her peer, thus creating a shared representation of events and objects. The understanding of this shared representation and intention might facilitate understating the intention of the researcher by showing the functional tool. Thus, the dyad could more easily combine that information with the task goal. New Zealand dyads were numerically better in tool innovation than Turkish dyads probably due to the cross-cultural differences along the individualist/collectivist dimension; however, this needs to be further investigated with a larger sample size. Another reason may be the linguistic difference in understanding the pronoun 'you' in the instruction for collaboration. We argue that there is a common recursive mechanism underlying both social and representational processes, which help us to be creative and innovative (Corballis, 2014). However, the recursive process in tool innovation may be positively or negatively affected by developmental and experience-related perceptual motor factors. As a complex behavioral pattern, tool making has not been systematically investigated including perceptual-motor, representational, and socio-cultural processes. With its multidisciplinary perspective in psychological sciences, we believe that this thesis will provide an insight into the evolution and development of creative human cognition and material culture.

6.2. Limitations

We have already discussed the limitations of each experiment in the last sections of each chapter (Chapter 3, Chapter 4 and Chapter 5). So that, here, it would worth value to discuss the things that has not mentioned throughout the last sections. There are some other limitations that has not mentioned in the chapters of the studies.

In Experiment 1, the age range of the 3 and 4-year-old group is wider that the older comparison group. This limitation might have affected some results, especially in sense of age comparisons between the older and the younger age groups. Secondly, although inhibition latency was predicting tool manufacturing scores, it is hard to indicate how actually the inhibition capacity come into operation. Thirdly, although we assume that hierarchical representation of the task elements in the hook task and hierarchical structuring are related processes, there is no clear goal in the hierarchical structuring task unlike in hierarchical representation of task elements.

In Experiment 2, the first limitation is that familiarity and salience of affordance results of the adult group would not be meaningful for the Experiment 3. Thus, generalizing and structuring the Experiment 3 according to the results of Experiment 2 would be misleading in some senses. Alternatively, future studies may ask familiarity of the tools to the children directly. Secondly, In the Experiment 3, the divergent thinking task were applied only to the wooden sticks group because of the various reasons explained in the Chapter 4. Alternatively, all the groups would have been given different tools.

In Experiment 4, when comparing individual and joint groups, we calculated the mean score of dyads for their predictor task. On the other hand, there were no dominance or curiosity measure that would help to identify the children who would contribute to the tool making process in each dyad. Although Experiment 5 is an explorative study that its results would help to construct clearer experimental studies in the future, our prediction based on cultural differences could not be valid in our sample. As it was stated clearly in the Chapter 5 and its supplementary materials, how the participants were recruited, the settings of the experiments (kindergarten vs lab), and the starting age of the primary school education were different between two cultures. So that, results should be interpreted very cautiously.

Researchers has just started to understand the factors affecting tool making during childhood. However, studies are still very limited. Below, we outline four limitation in the development tool innovation and tool making literature.

(1) Tool making (including tool innovation) is an intricate subject, because of the fact that there are many factors working in tandem through the process of tool innovation (Reader, Morand-Ferron, & Flynn, 2016). First of all, we may need frameworks that we could shape our hypotheses on them. Frameworks on the phylogeny of tool making and innovation are abundant, but there is only one framework (as far as we know) explaining the development of tool innovation.

(2) Does tool innovation really require insight in children? Unfortunately, we could not answer that question clearly, as our study design (nor the designs in the literature) allow to reveal any possible contribution of insightful learning in tool innovation in children.

(3) We still don’t know why children have great difficulty in tool innovation. We addressed that issue several times throughout the chapters, and we argued that the idea of a tool may precede manipulation of a tool. However, how can this hypothesis be tested?

(4) We clearly demonstrated that dyadic action facilitated tool making process. However, we could not answer what really changed (representationally) from the individual tool making to dyadic tool making. On the other side, even though it was not significant, there were numerically more dyads who could innovate a tool. Our observations suggested that how children were approaching the hook task were actually different. How did these children represent the task elements and their role in the task context?

In the following four sections, we will address these limitations and provide solutions for them. They are all open topics for future research.

6.3. A framework for on the ontogeny tool innovation

Frameworks have an indispensable role for any scientific topic. They are the bird-eye-view of the topic, proving the first glance of possible factors and interactions in a mechanism. Very recently, Carr, Kendal and Flynn (2016) suggested a framework represented in Figure 31. All the terms that is used in their pathway are explained throughout the thesis. They indicate that this pathway is for individual-level innovations. They argue that the pathway move from left to right, each pathway sequentially direct to the next construct. As we will construct our framework base on the one suggested by them, below we gave the explanations provided by them. Carr, Kendal and Flynn (2016) make seven suggestions for behavioral innovations in physical realm:

Point 1. “Innovation can be the result of asocial learning or a combination of asocial and social learning, but it must be novel” (p.1508).

Point 2. “There are a number of hypothesized contributors or precursors to the innovation process. These include, but are not limited to, causal understanding, insight, curiosity, exploration (discovery learning), divergent thinking, and creativity. They do not equate to innovation and alone are not sufficient to produce it”(p.1510).

Point 3. “Functional fixedness (conservatism), low motivation, pedagogy, and neophobia restrict innovation”(p.1511).

Point 4. “Innovations, being of multiple origins, may be cognitively distinguished (p.1512).”

Point 5. “Goal emulation can represent a weak form of innovation (p.1513).”

Point 6. “An innovation should be useful and/or transmitted (p.1514).”

Point 7. “An innovation need not reflect intentionality, but it should lead to learning” (p.1514).”

We aggree with most of these points, and we have made simmilar suggestions throughout the thesis based on the extand ontogenetic and philogenetic literature. However, we believe that they ignore some main factors that we showed as important factors in tool innovation and tool making.

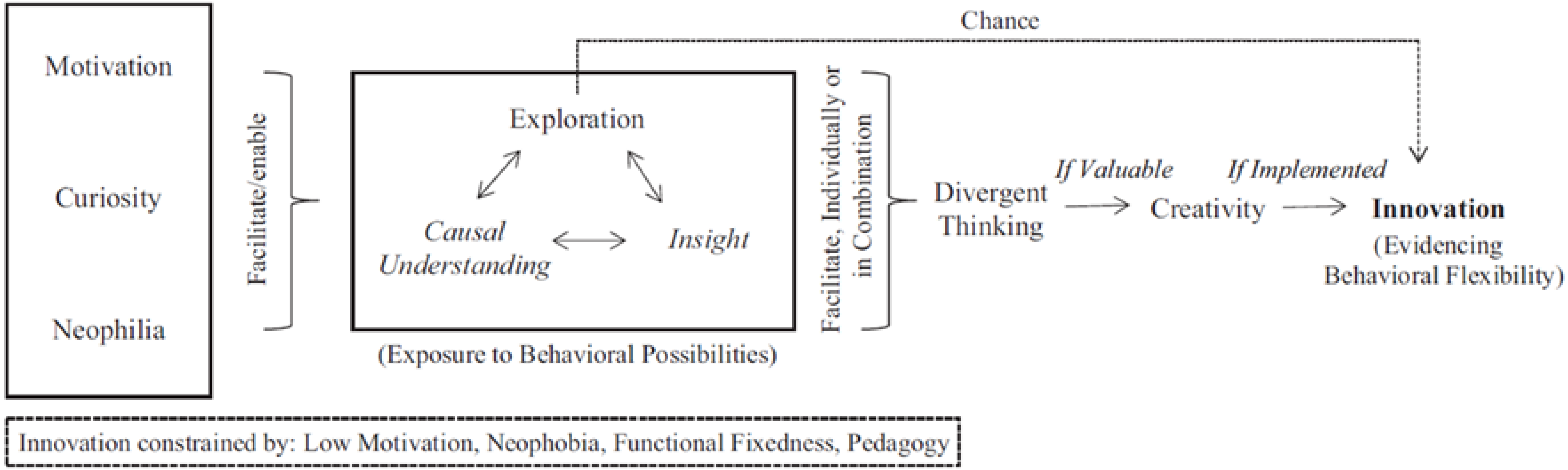

Figure 31: Tool innovation framework offered by Carr, Kendal, and Flynn (20). From "Eureka!: What is innovation, how does it develop, and who does it?" by K. Carr, R. L. Kendal, E. G. Flynn, 2016, Child Development, 87(5), p. 1512. Copyright © 2018 John Wiley and Sons. Reprinted with permission.

"A hypothetical individual-level pathway to innovation. Arrows denote which construct leads to another construct. From left to right, any of the processes within the first block can lead to those within the second block. The constructs in italic text within the second block play more contested, or less direct, roles in this pathway (see Point 2). Neophilia, and its opposing construct neophobia, are discussed in Point 3. Context and prior learning (social and/or asocial) are acknowledged to potentially contribute to each construct portrayed and to differentially promote behavioral change. Innovation is generally regarded as a component of behavioral flexibility by allowing "individuals to react to environmental changes. . . [by] changing established behavior" (Toelch et al., 2011, p. 1). It should be noted that, rather than necessarily prompting divergent thinking and creativity, exploration may allow an individual to stumble upon an innovation by chance, captured by the connecting arrow" (p. 1512).

First of all, motivational factors can be gathered in the same construct, such that increase or decrease in these factors might affect the next construct. In any case, they are all related to the children's tendency while approaching a task or tools. Second, they list some suggested factors that might constrain innovativeness. However, the relation between these factors are not clear from this construct, nor from their article. Beyond that, functional fixedness and pedagogy does not always constrain innovativeness. If the relation between tool and the task triggers a kind of action, innovativeness might emerge (see our results with soda straw in Experiment 3). Secondly, the factor of chance might be redundant in a framework. Although chance is an important source for novel behaviors, it is still under debate whether chance should be considered as innovation or not. Third, they argue that how children represent and control over these representations, and psychological mechanisms related to the generalization (divergent thinking and creativity) are sequential processes. However, we believe that representational processes and generalization processes work in parallel. They both may or may not contribute to the insightful learning. Fourth, we argue that there might be one more step before innovation in the behavioral realm. Lastly, the role of hierarchical structuring of sequential stimuli and inhibition are ignored in their framework.

Based on these critiques, we suggest an individual-level framework depicted in Figure 32. According to this framework, there are six main steps in the process of tool innovation:

Step 1: **Motivational factors**

These factors are listed in section 2.5.1. These factors are related to the motivation of children compared to other ones. These factors are the tendencies of the children which mostly base on personality differences and control of emotional responses. Neophilia and neophobia, curiosity, and the motivation to direct exploration (mostly with hands) can be counted in this group. Contribution of these factors to innovation in comparative sciences well studied (see 2.4.1). However, we literally know very little about the effect of these factors on any kind of innovation during childhood. Future research is needed to clarify the effect of motivational factors.

Step 2: Social learning and perceptual-motor repertoire

This construct is mostly related to *long term memory resources* (procedural and semantic). Children have a personal life history with objects, and objects' relation with the environment. They have an accumulated knowledge on the affordance of tools and task elements, and different social information related to them. While they have socially learn to use some tools in a demarcated context (e.g. spoon), some tools are novel but still they have the capacity to attain a function to them especially after the 4th year of age (see Defeyter, & Gelman, 2003; Casler & Kelemen, 2005; Defeyter, Hearing, & Gelman, 2009). As for learning artifact categories, even 3-year-old children have a developed capacity to attain a category for tools base on their functions (Phillips, Seston, & Keleman, 2012). When children are presented with a task, they will probably try to solve the task with the resources that is already in their repertoire. In the hook task, many children attempted to insert their hand into the tube to get the bucket out. However, the size of the upper part of the tube did not permit them to insert their hands inside. This action pattern is expected, because reaching behavior is one of the first developing abilities, and it is already in their action repertoire. They insistently try to use the tools as they are, namely without changing their shape. While manipulating objects is common in childhood, changing the shape of a tool to solve a novel problem might not be that common.

Previously learned (socially or via self-learning) behaviors affect children's tool making process, and we have discussed it throughout the chapters. What is to the point is that action and perception might not be that separated during childhood. Perception of tools might trigger some possible actions and action consequences, based on their repertoire. This might lead to consider *ideo-motor perspectives* on tool-related behaviors. Our experiments with the wooden sticks showed us that children insistently tried to use the long wooden stick. It might be claimed that children's anticipation of action consequences for using a very rigid tool might be using it as-it-is, because rigid tools generally afford to catch things without any further manipulation on it.

We believe that this construct greatly contribute to the further constructs, either in a constraining or constructive way. The next step is the parallel processes between representational and creative factors which might or might not give rise to insightful learning.

Step 3: **Representational factors, creative factors (generalization) and insight**

Although children's repertoire is a great resource for approaching to the tasks and tools, as it was stated, these resources are not enough to solve novel problems. Innovative problem solving, as the name implies, requires to find new solutions to old problems or solutions to novel problems. Thus, the task elements should be represented first.

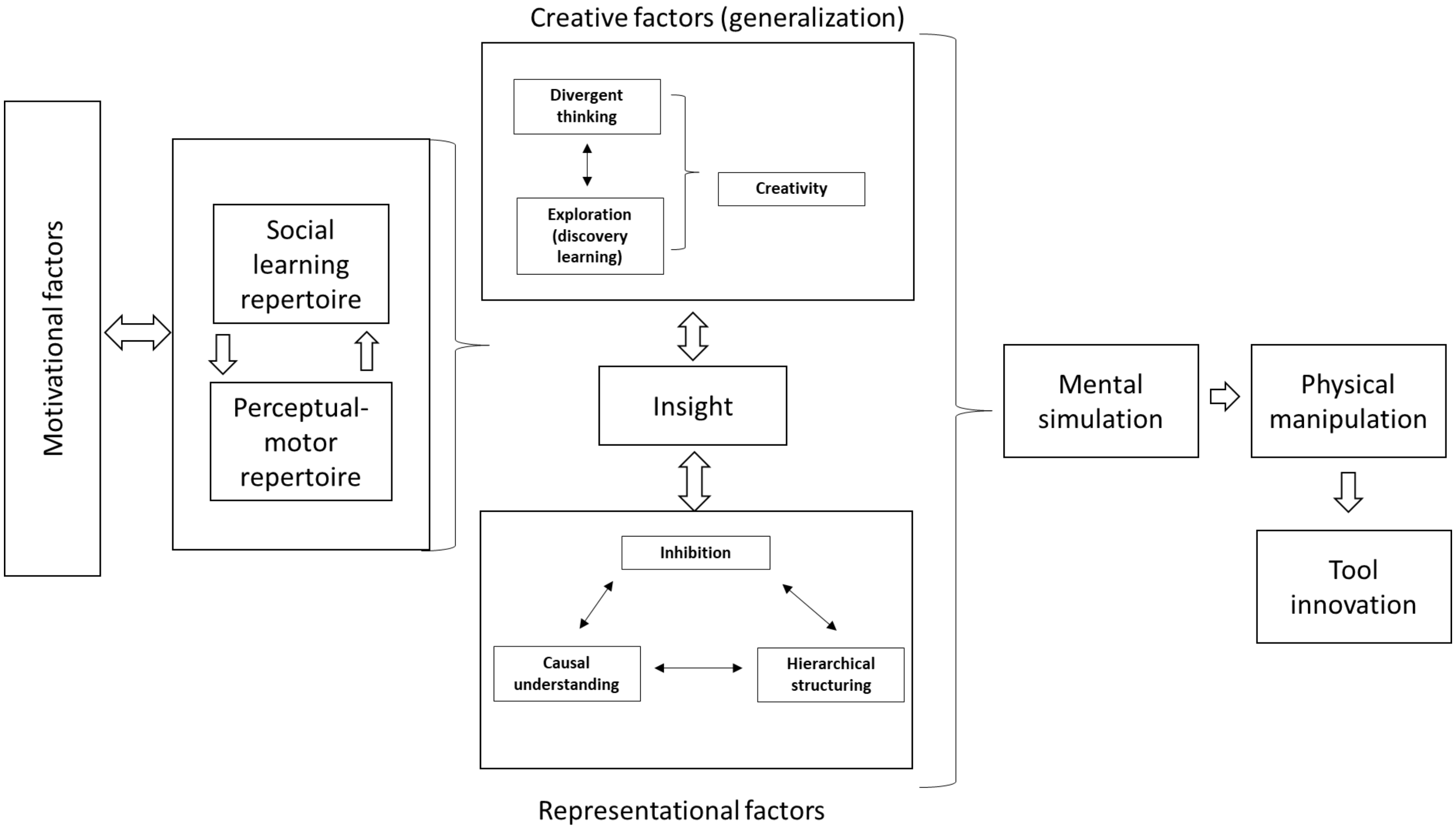

Figure 32: A sugested framework for tool innovation.

Children can make simple causal relations between elements of the tasks. For instance, in the hook task, children can understand the relation between the tool and the task, and the relation between the sticker and the bucket. However, they should go beyond simple causal relations, and represent the task elements and the role of each tool hierarchically related to the goal. However, children should also inhibit prepotent responses. For instance, if a selected tool (a piece of string) does not work, they should switch to the other available tools, e.g. pipe cleaner. Representational capacities might be affected from long term memory resources of children. For instance, if they are familiar with the tool and possible limited action repertoire with the tool, they should inhibit these prepotent responses.

However, merely making hierarchical representations may not be enough for innovations. In parallel, children probably generalize the function and role of task elements, which we call creative factors or generalization. Among others, a similar term is provided by Knudsen et al. (2016, p.214) – *novelty generation*. They define novelty generation as "the ability to flexibly and adaptively generate products that are unique".

During the hook task, children touch tools and probably contemplate the very relation between the tool(s) and the task. In other words, they explore the materials in sense of their relation to the task. This kind of exploration is different from basic haptic exploration which is only related to the properties of an object. Carr, Kendal and Flynn (2016) define it as *discovery learning*, and here we use this term in the same sense. Children may discover the relations among the task element. On the other side, children with better divergent thinking abilities might go beyond the perceptual array. Therefore, divergent thinking is a very potential source for innovations. Our results are also in parallel with this prediction. Their solutions during discovery learning and divergent thinking may or may not be *creative*. However, both divergent thinking and explorative learning can be subcomponents of creativity. Divergent thinking and creativity are closely related to novelty, innovation and intelligence (see Hocevar, 1980; Runco, 1991; Walach & Kogan, 1965; Gilhoody, Fioratou, Anthony, & Wynn, 2007). Although these terms are very charming, they are still very vague and the mechanism underlying these processes are not very well-know. However, we should not ignore these processes and their contribution to the innovativeness just because mechanisms underlying them has not been clarified yet. In the last decades, cognitive scientists suggested the term *recursion*. Actually, the term of recursion has flourished a fruitful interdisciplinary research programs in cognitive and developmental science (see Miller, Kessel, & Flavell, 1970; Eliot, Lovell, Dayton, & McGrady, 1979; Hoffecker, 2007; Corballis, 2007; Brattico, 2010; Valle, Massaro, Catelli, & Marchetti, 2015). In section 5.2.2, we briefly mentioned about the possible link between recursion and creativity.

From the motivational contract to the representation and generalization process, children might solve a problem requiring innovativeness merely base on the perceptual-motor properties or the tools and the task during the process. They may accidentally bend the tool and immediately realize the relation between the bent tool and the task. This might be considered as a low-level innovation. However, they may see the relation between task elements and suddenly realize a functional solution. In that case, it is probably *insightful learning*. There are two problems here: firstly, designs of tool innovation studies could not allow the effect of insightful problem solving systematically; and secondly we need a design that can separate perceptual-motor feedback and social learning from insightful problems solving. In section 6.3, we offer are study design that might unravel any possible effect of insight into tool innovation.

At the discussion parts of our studies, we argue that mental simulation of an ideal tool precede physical manipulation of a tool. However, this hypothesis should be carefully tested. In Section 6.4, we ground our hypothesis and suggest a design that this hypothesis could be tested.

6.3. What is the role of insight in innovation? How can we investigate the relation between insight and tool innovation?

Insightful problem solving has been defined as the process of combining various pieces of information in the context of a task mostly unconsciously (offline), often coming up with the solution of the problem in a sudden 'Eureka!' moment (Mayer, 1995). This terms was dubbed by Wolfgang Köhler (1957) when he observed apes' tool-related problem solving, e.g., putting one box on top of another box and climb on them to fetch a banana with a stick. Köhler realized that some chimps were solving such tool-related problems sometime after they had been exposed to the problem and some failed attempts. He indicated that the solution appeared in a sudden way while apes did not deal with the problem. In a similar vein, Bird and Emery (2009) emphasized the role of insightful problem solving in innovative tool modification by rooks using a task which was originally used by Weir, Chappel and Kacelnik (2002) to test physical cognitive abilities of New Caledonian crows. As we stated, in this *hook task* some rooks were able to bend a wire into a hook shape to retrieve a bucket baited with food from a transparent bottle. We also indicated that it has been shown time and again that children cannot solve a similar task, e.g., retrieving a bucket from a tall transparent tube by making a hook with a pipe cleaner to obtain a sticker inside the bucket, before the age of seven or eight (Beck et al., 2011; Cutting, Apperly, Chappell, & Beck, 2014). However, a major problem in these studies is that children are only given a very limited amount of time (1 minute to 3 minutes) to solve the task. Thus it might be inappropriate to speak of insightful problem solving, as insight might require some time for offline processing in such a way that pieces of information can be assembled through representational change (Kaplan & Simon, 1990) and memory consolidation (Robertson, 2009). In other words, insight may not occur immediately, but sometime after exposure to the task. It is known that offline processing during memory consolidation may happen during wakefulness and sleep (Robertson, 2009). However, sleep triggers insightful learning through representational change more than wakefulness in adults (Wagner et al., 2004). Thus, tool innovation tasks might be given to children before and after a break. During that break children may get a nap, or may have a task break, which could help to reorganize their representations.

6.4. Does the idea of a functional tool precede tool making?

(1) Based on the claims of ideo-motor theory (see, Stock & Stock, 2004; Paulus, 2014), it may be argued that preschool children can predict the outcomes of their actions during tool use and tool making after observing modifications, and they can use their repertoire of bidirectional action and action-consequences while predicting the outcomes of future actions. In this way, they can select a functional tool (e.g. selecting a hooked pipe cleaner; Beck et al., 2011), use their perceptual-motor repertoire to make a tool (e.g., seeing a functional example tool; Neldner, Mushin, & Nielsen 2017; Cutting et al., 2011), or implement tools based on the observed actions (Cutting et al., 2011) during the tool innovation process.

(2) “Ideo-motor Recycling Theory” claims that tool use, language and foresight abilities share similar perceptual-action mechanisms (Badets & Osiurak, 2017; Badets, Koch, & Philipp, 2016). On these grounds, reasons may be provided how children can use their perpetual-motor repertoire for facilitating their tool making process. First, they may be better in tool making with a soda straw because this is a familiar tool which is in their tool repertoire (Chapter 4). Second, they may gesticulate and/or articulate the possible solution for the task, e.g., by clearly saying that a bent-cane would work to solve the bending task or showing a ‘hook’ shape.

(3) Although children can represent and simulate a functional solution for the *bending task*, they may not be ready to turn these simulations into actions, in other words manipulate a novel tool spontaneously to solve a problem (tool innovation). There are two critical points here: mental manipulation and mental simulation capacities of children. Preschool children can combine different images mentally into a coherent form or reorganize their mental images (Brandimonte, Hitch & Bishop, 1992). This ability is called "mental manipulation" or "reinterpretation". It denotes the capacity to reorganize, reinterpret or manipulate mental images (Finke, 1989; Finke, Pinker, & Farrah, 1989). Both adults and children can envision future events and remember past event with a similar brain network extending from primary visual areas to premotor cortex, which is called the "default network" (Østby et al., 2012). Results of Ünal and Hohenberger (2017) indicate that past and future episodic cognition in preschool children share similar cognitive mechanisms, and past and future episodic cognition is related to other cognitive abilities such as executive function, spatial working memory and temporal language in 3-to-5-year old children. It is also known that symbolic thought and creating mental images are early developing skills. Young children begin to interiorize the outer world and construct mental images providing control over representations even without perceiving the referent objects or events, which is called "reproductive mental images". The next phase of reproductive mental images is anticipatory mental images that provide control over presumptive objects and events. With the developing symbolic function, children get better in some cognitive and social abilities relying on symbols like language, pretense, gestures etc. (Taylor, 2005). Yet, preschool children may not be ready for spontaneous multi-modal processing (manipulating objects in a controlled way according to a goal) necessary for tool innovation, e.g., for changing the shape of an object such as a pipe cleaner.

(4) Tool innovation might require two crucial skills: spontaneous creativity for solving a problem and controlled tool making. Studies on spontaneous creativity define two main regions in the adult brain: a premotor area in middle frontal gyrus and parietal areas (for review, Forgarty, Creanza, & Feldman, 2015; Gonen-Yaacovi et al., 2013; Dietrich & Kanso, 2010). While the former area is activated during action planning and following abstract rules, the latter areas are associated with multimodal and spatial processing (Forgarty, Creanza, & Feldman, 2015). Beyond these areas, anterior cingulate cortex, which supports conscious control of action, also plays a crucial role in insightful problem solving (Dietrich & Kanso, 2010). On the other hand, tool making activates areas responsible for spatial cognition, motor and multimodal processing, and visual associations such as superior parietal areas, central sulcus, postcentral sulcus, and cerebellum (Stout, et al., 2000). Covering the wide range of results, children may not be ready to act according to their representations spontaneously, which might require developed conscious control over multimodal information and hierarchical action control. The parietal lobe and motor parts of the frontal lobe are crucial for executing hierarchical actions and multimodal processing. Tool innovation via changing the shape of tools might require developed *frontal-parietal network*. Thus, it can be inferred that children might be ready to control their mental images creatively (mental manipulation), though it might be too early for them to control their actions according to their simulations (physical manipulation) in tool innovation tasks.

Based on these four points, children's performance on mental manipulation tasks and tool innovation tasks can be compared. On the other side, if children can simulate functional tool, they can say what kind of tool it might be. Thus, asking children what kind of tools would work to solve the target innovation task might be helpful. Alternatively, children may be asked to draw their opinions. On the other side, an adult may show the target tool with hand gestures (e.g., drawing the target shape on the air with his finger). If children have a mental representation of the target tool, the hand-gesture of the adult experimenter could facilitate tool making.

6.5. Peer interaction and tool making

In the first three experiments, individual children were trying to solve the hook task. We have already represented the hierarchical representation of the task solution related to goal in Chapter 2, and showed that the complexity of their hierarchical structures are predictors of their tool manufacturing results. Their difficulty in spontaneous tool innovation is so evident that we it is even not dependent on the type of the tool nor being in dyadic interaction. Nevertheless, we showed that dyadic interaction facilitates tool manufacturing. But why? Why not in the first phase but in the second phase? We believe that this question might be answered with digging three critical points.

(1) First, children's are yet not ready to make novel tools spontaneously, as it requires controlled tool making and hierarchical multimodal processing according to abstract rules which is closely related to the development of fronto-parietal network (see sections 3.5.4 and 6.4). We stated that they can use tools easily. Let us consider the tool use example given by Tomasello et al. (2005), which is shown in Figure 33. In this representation, someone has an

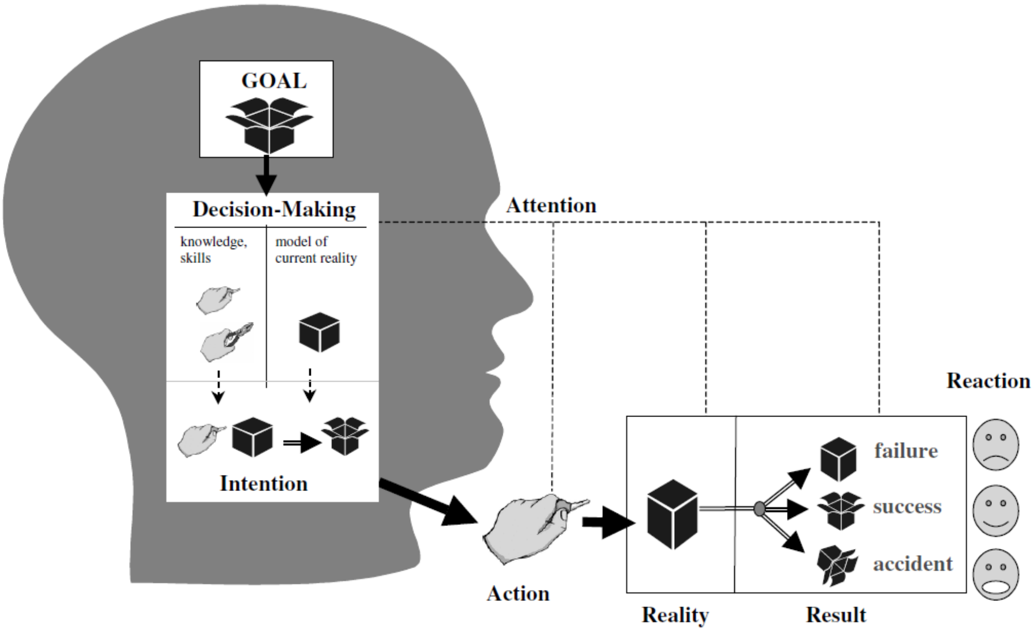

Figure 33: Individual tool use. From "Understanding and sharing intentions: The origins of cultural cognition" by M. Tomasello, M. Carpenter, J. Call, T. Behne, & H. Moll, 2005, Behavioral and Brain Sciences, 28, p. 677. Copyright © Cambridge University Press. Reprinted with permission.

intention to open a box via using a tool; namely the goal is to open the box. During the decision making process of tool use based on the intention of opening the box, she also uses the knowledge and skills to understand the task demands and using the tool, and she models the current reality. Her attention will be on tool using action on the tool, which might be resulted with failure, success or there may be an accident. Eschewing the emotional reaction based on the result of the action, this individual tool use process can be more or less done by a four year old children. However, some four year old children cannot make a tool even after the social demonstration of tool making action, namely *tool manufacturing*. If the tool making is cognitively more demanding (combining two wooden sticks) even 5-to-6-year old children have difficulty in manufacturing a tool (tool making after seeing a ready-made tool). But, as we have repeated again and again, dyadic interaction facilitated tool manufacturing. How? They cannot manage to innovate a tool even in dyadic interaction, but they can manufacture a functional tool in dyadic interaction.

(2) This situation might be explained based on motor and perceptual resonance. In Experiment 4 and 5, in the dyadic interaction groups, while one of the peers (peer-1) were using a tool another one was watching her peer (peer-2). Although peer-2 was only watching peer-1, perception might have trigger her action repertoire. This is called as *motor resonance* (see Schütz-Bosbach, & W. Prinz, 2007; Paulus, 2012), and existence of a system like that is greatly supported by mirror neuron system (for reviews see Rizzolatti, Fogassi, L., & Gallese, 2001; Rizzolatti, Fadiga, Fogassi, L., & Gallese, 2002; Paulus, 2012). On the other side, action production of the peer-1 might “prime perception in a way that observers are selectively sensitive to action-related events in the environment and similar actions of conspecifics (Schütz-Bosbach, & W. Prinz, 2007, p.349).” This is called as perceptual resonance (Schütz-Bosbach, & W. Prinz, 2007). Note that dyads were sharing the tools; that is to say, most of the time it was not the case that only one peer was only observing and the other was acting. Therefore, both of the peers were most probaly having perceptual and motor resonance (see Figure 34). These motor and perceptual resonance migh have facilitated understanding the conspecific, namely the experimenter’s showing a ready-made hook.

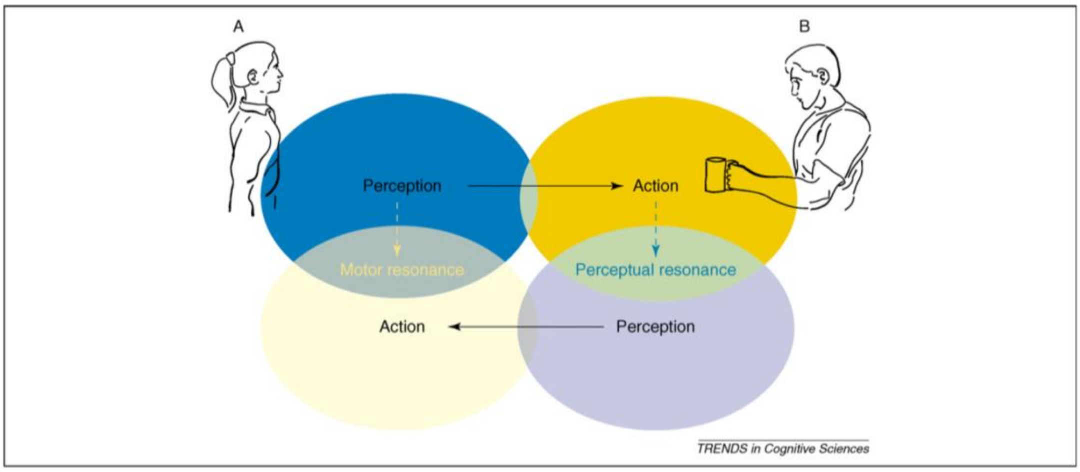

Figure 34: Perceptual and motor resonance. From "Perceptual resonance: action-induced modulation of perception" by S. Schütz-Bosbach, & W. Prinz, 2007, Trends in Cognitive Sciences, 10(2), p.350. Copyright © 2018 Elsevier. Reprinted with permission.

(3) Although motor and perceptual resonance help us to understand how dyadic interaction might help solving the hook task after the social demonstration of the ready-made tool of the experimenter, it does not tell us how dyads were keeping elements of the task in mind and how they were interacting together to solve the task. Giving the task to the dyads and telling them that the goal is to get the sticker, it might create a 'perceptual common ground'. In this common ground they might coordinate their actions via predicating each other's action, sharing their representations and integrate action predictions with the visible actions of conspecifics (see Sebanz, Bekkering, Knoblich). However, in this common ground, they also should consider the hierarchical structure of the task elements and plan their motor behaviors accordingly. We know that 5-year-old children are not good at anticipating other's role in a task and act accordingly during tool use, but they can learn to do so easily (see Paulus, 2016). However, if one of the children (or both children) in dyads have a good capacity to represent hierarchically, they can finally merge the task elements after the social demonstration of the experimenter. This stream of reasoning is in line with the claims of Tomasello et al. (2005). As it is shown in Figure 35, two person might attend to the same same goal jointly while representing this joint goal and the elements of the task. Our results of the Experiment 4 were in parallel with this argumentation. As a summary, we may argue that the dyads were better than individuals in tool making thanks to both perceptual-motor resonance and each children's understanding the goal and representing the task elements hierarchically.

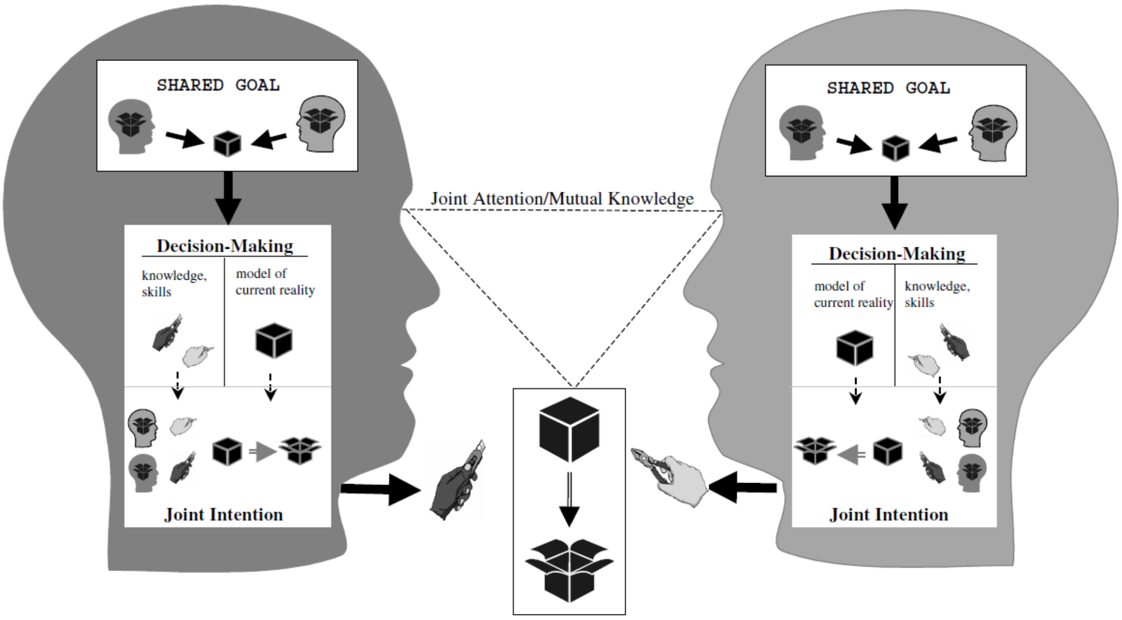

Figure 35: Dyadic tool use. From "Understanding and sharing intentions: The origins of cultural cognition" by M. Tomasello, M. Carpenter, J. Call, T. Behne, & H. Moll, 2005, Behavioral and Brain Sciences, 28, p. 681. Copyright © Cambridge University Press. Reprinted with permission.

Although not significant, we found that there were more tool innovators in New Zealand dyadic group compared to Turkish dyads. This might be related to learned cultural norms, we suggested. We noted that the hook task did not require joint interaction, though. However, Turkish children might have represented the task as if it required collaboration. Children from an individualistic country may represent the task as an obligatory collaborative task. We suggest a representation given in Figure 36. According to this Figure, representation of and individual of the task contains the relation between the target and the tool, and the intermediate steps between these two should be constructed by the individual. However, children from a collectivist culture may represent the task as a collaborative activity. So that they would automatically share the given tools or use the same tool interchangeably. However, the shared representation might be different for children coming from an individualistic country. Along with understanding that they were presented the task together, and representing the perspective of each other, they may not think that the task require a collaboration. These are big claims and they should be tested with much bigger sample sizes considering contribution of different factors.

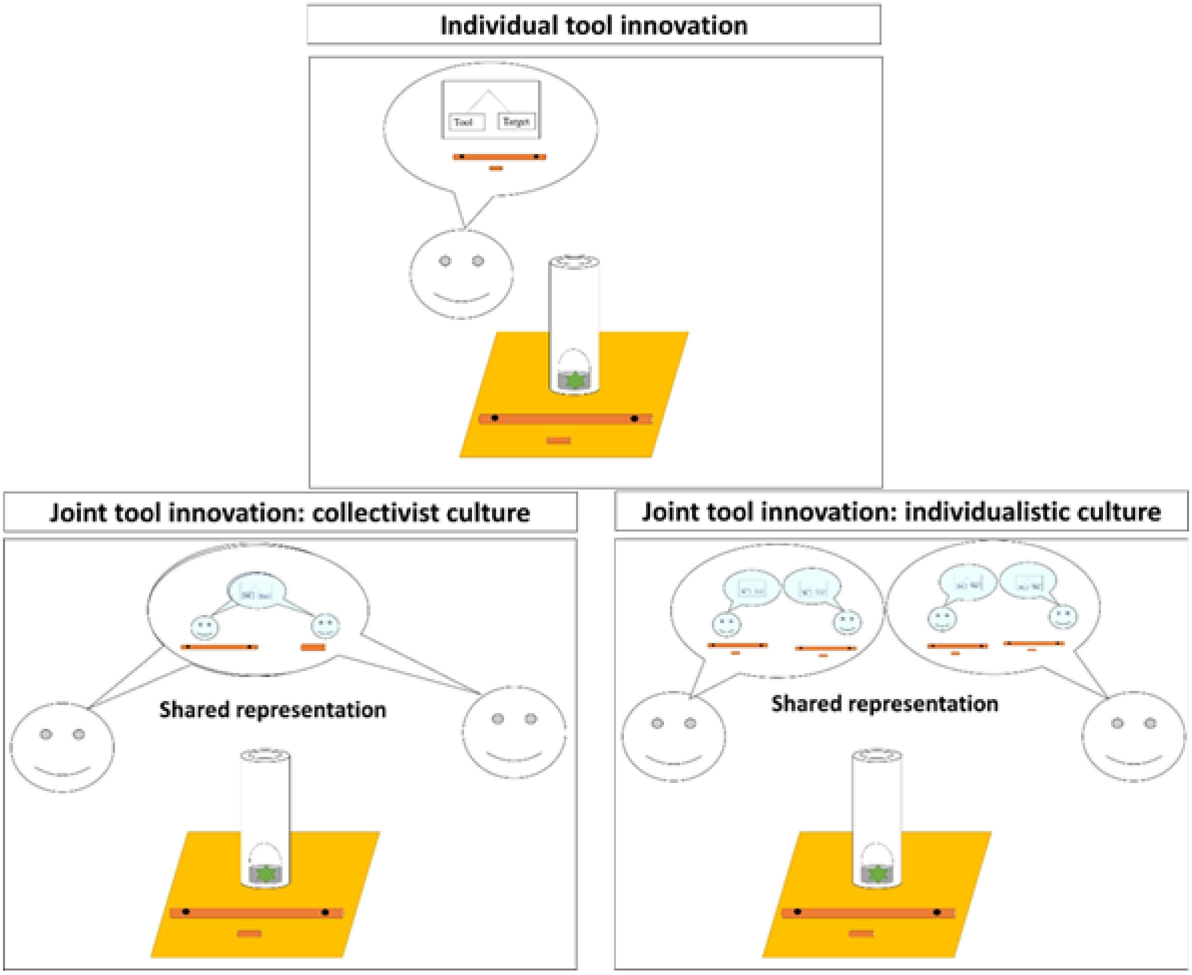

Figure 36: Representation in individual and joint tool innovation.

6.6. The big picture: Phylogeny, ontogeny and cognitive science

In order to answer some questions about cognition, cognitive scientists should consider both the developmental and evolutionary processes. Ontogeny of a child might help to understand some core discussions in cognitive science such as modularization, innate tendencies, the nature of representations and concepts, and the role of learning and maturation in cognition (Keil, 2006). This has been extensively done in language development (see Gathercole & Hoff, 2007; Saffran & Thiessen (2007) and development of categorization (see Gelman & Markman, 1986), but tool-related behaviors are largely are ignored

(Keen, 2011). However, the ontogeny of cognition has a growing interest in cognitive and biological sciences (as an example see Laland et al., 2015).

Evolution of cognition has a long history. If we want to understand the structure of cognition, we cannot ignore this evolutionary past (Dennett, 1988). Without coming back to the biological and anthropological past (phylogeny), we might not be able to understand how the mind works. Now we have a great bloom of research programs on the ontogenetic and phylogenetic origins of cognition, and theoretical formulations considering both ontogeny and phylogeny of cognition (see Blasi & Bjorklund, 2003; Fitch, 2014; Gómez, 2004; Seed & Tomasello, 2010; Amati & Shallice, 2007; Cruse, 2003; Horik & Emery, 2011; Bender, Hutchins & Medin, 2010).

We believe that tool-related behaviors are great resource to understand how the non-human and human mind works. Tools are so inherent in human cultural evolution, and human children grow in this rich tool culture (Tomasello, 2009). As it is also indicated in this thesis, we are a very innovative specie, but somehow this innovativeness develop late. Innovation is closely related to higher order cognitive mechanisms such as problem solving and intelligence (see Griffin and Guez, 2014); therefore, it might help us to unravel the 'mystery' of cognition. The topic of innovation is very rich in biology, which give rise to compare non-human animals with human.

Lastly, we should be aware that neither children are pre-adults (see Norman, 1980) nor 'adult human' is the only animal who have cognitive abilities, as we gave examples from birds and other primates. Future research may help to further clarify these issues and demolish human adult-oriented view in cognitive science, which is ones called 'adultcentricism' (see Goode, 1986). I would call it as 'adultomorphism', which is also very common in developmental psychology.

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APPENDICES

APPENDIX A

SUPPLEMENTARY MATERIALS OF CHAPTER 3

Supplementary material 1

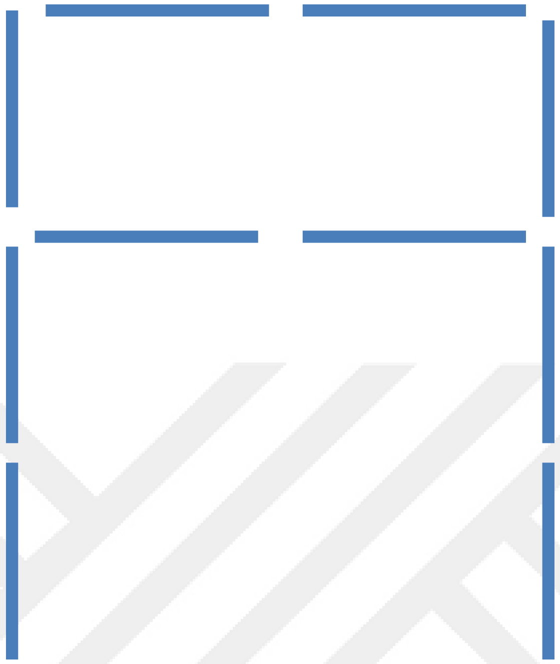
Hierarchical tree structuring task

Three measures were used to measure hierarchical structuring capacity: Hierarchical resemblance, hierarchical complexity, and tree structuring processing time. Our complexity measure was based on the following explanation: “One possibility was to assess complexity in terms of branching structure. But because many of the younger children’s structures did not resemble trees, we looked at mathematical graph theory for a more general way to describe the mobiles. In graph theory the junction of two or more lines is called a ‘node’. If two lines join, the node is of ‘degree’ 2; if three join, degree 3; and so on. The end of a line to which nothing is joined is called a ‘terminal node’ and is of degree 1. By squaring the number of degrees, more complex nodes were given heavier weight” (Greenfield & Schneider, 1977, p. 304). The only difference with the complexity measure used in the current study was the middle junction, with which we tried to obtain a more sensitive measure of complexity. For example, if the participants could correctly do the middle junction (with complexity degree 3), they obtained a score of 3^3=27.

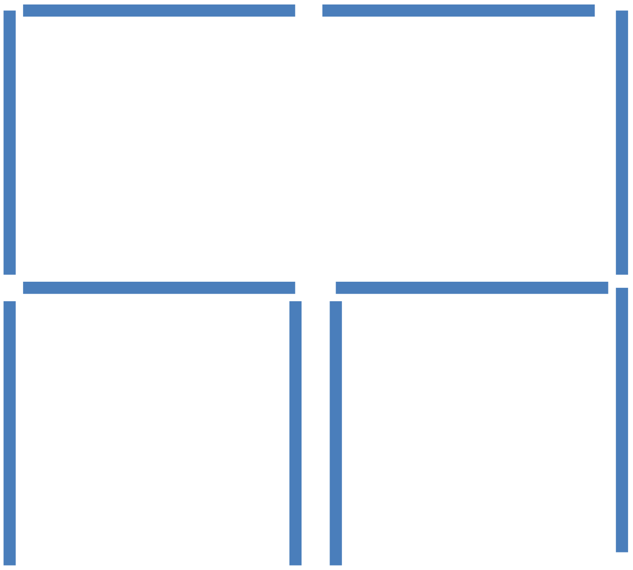
There are two main reasons why we used three measures of the hierarchical structuring task in the same model. First of all, there seem to be three main components of this task: (1) ‘surface veridicality’ of the copied structure with the model (hierarchical resemblance), (2) cognitive representation of the hierarchical structure (hierarchical complexity), and (3) the procedural and performative measure of the process (tree structuring processing time). Taken together, these three measurements might represent children’s overall competence in hierarchical structuring. The second reason is that the process of tool innovation might draw on those components in the construction behavior.

Supplementary material 2

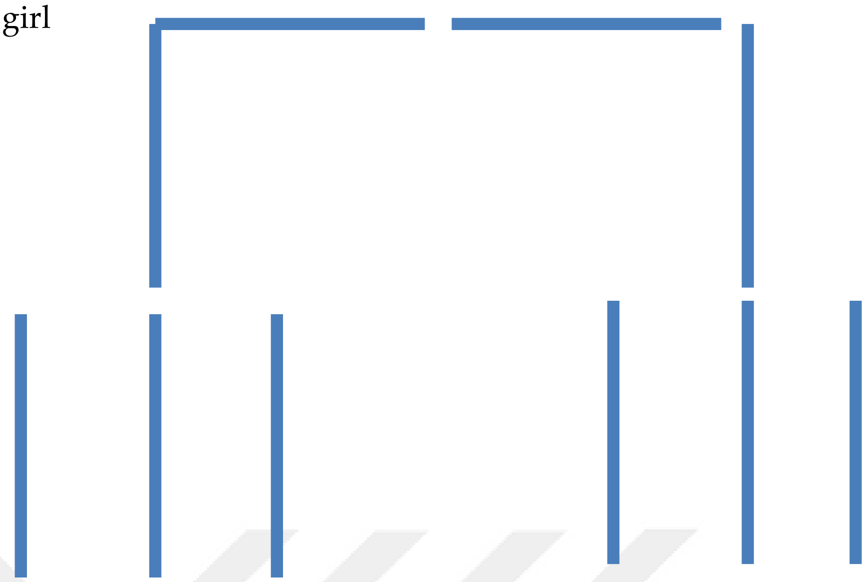
3.9 years old girl



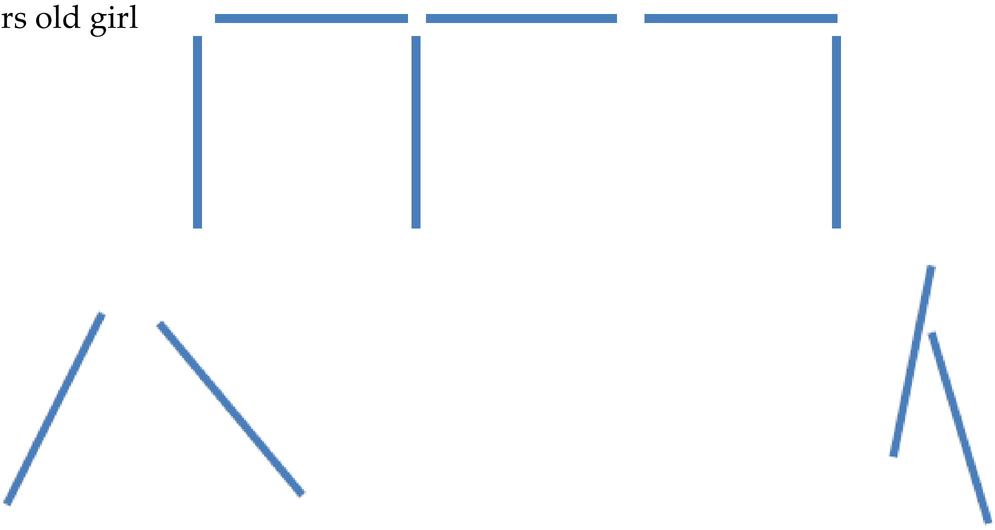
4.1 years old boy



3.2 years old girl

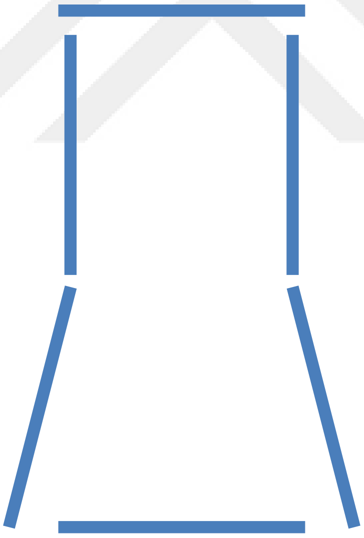


4.3 years old girl

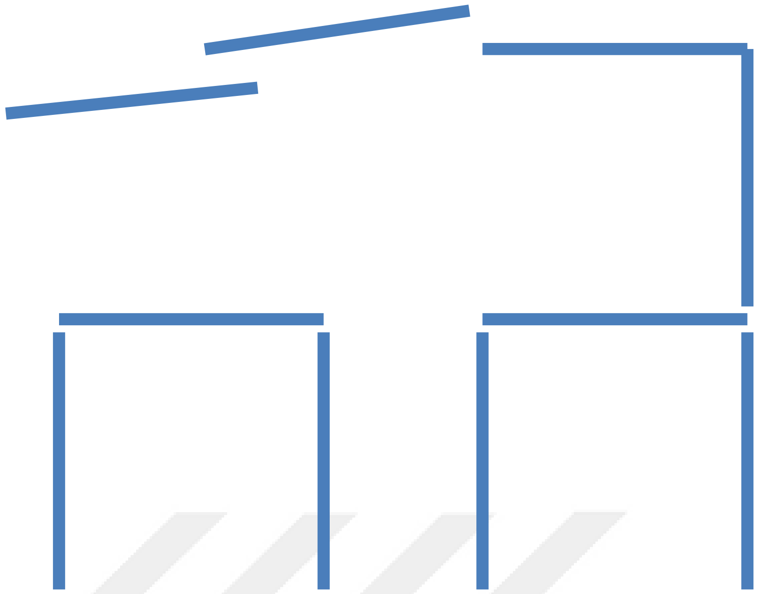


3.6 years old girl

3.5 years old boy

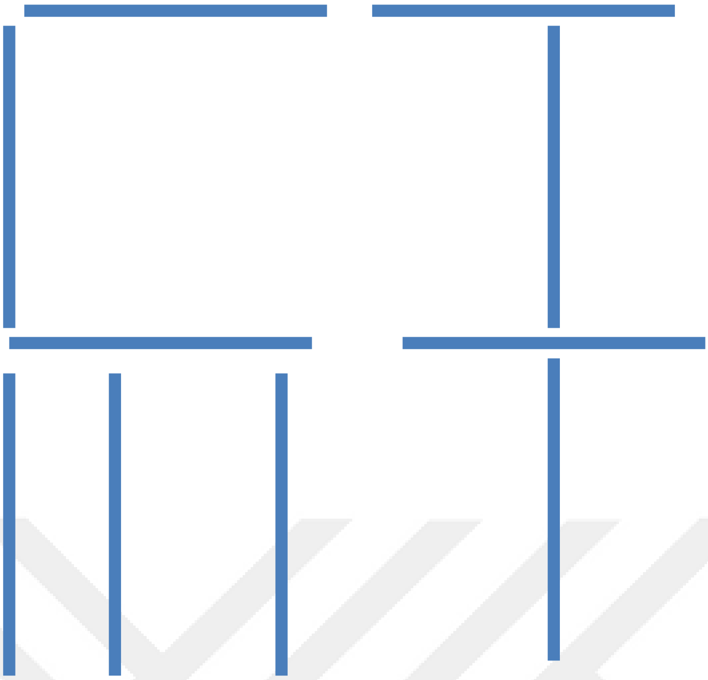


4.7 years old girl



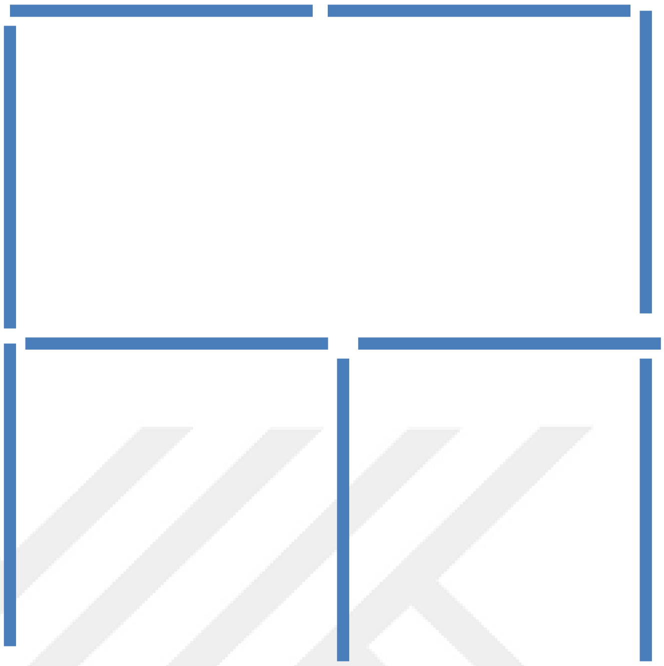
4.5 years old boy

5.6 years old boy



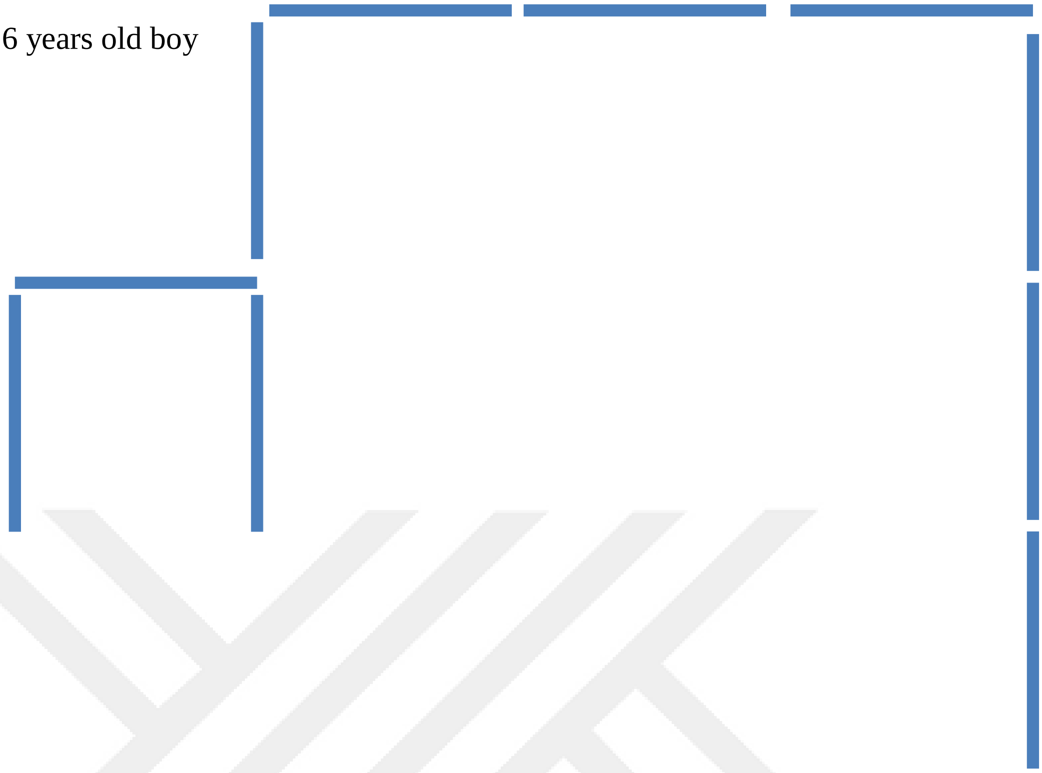
5.4 years old boy

5.6 years old boy

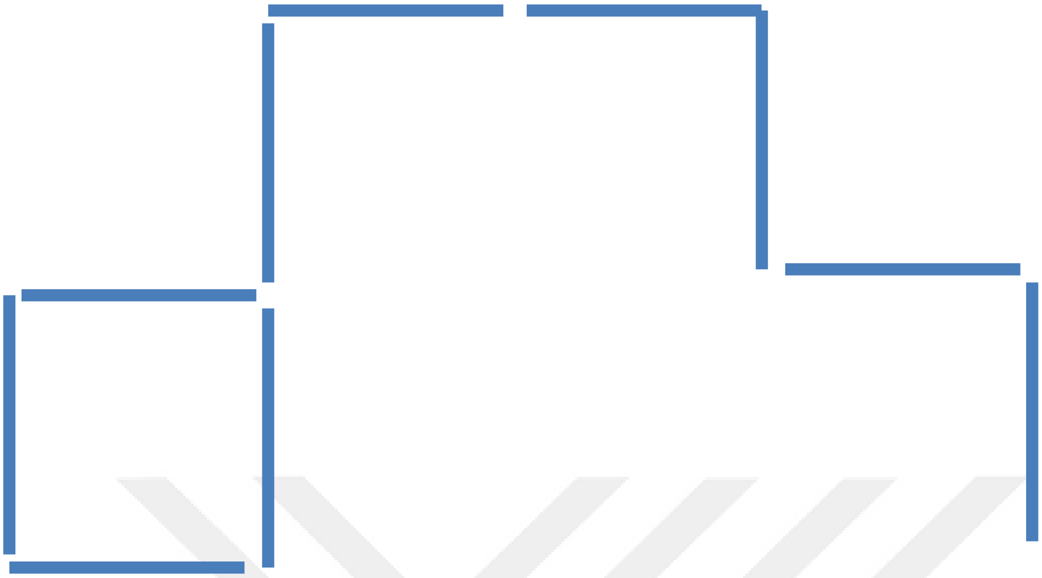


5.4 years old girl

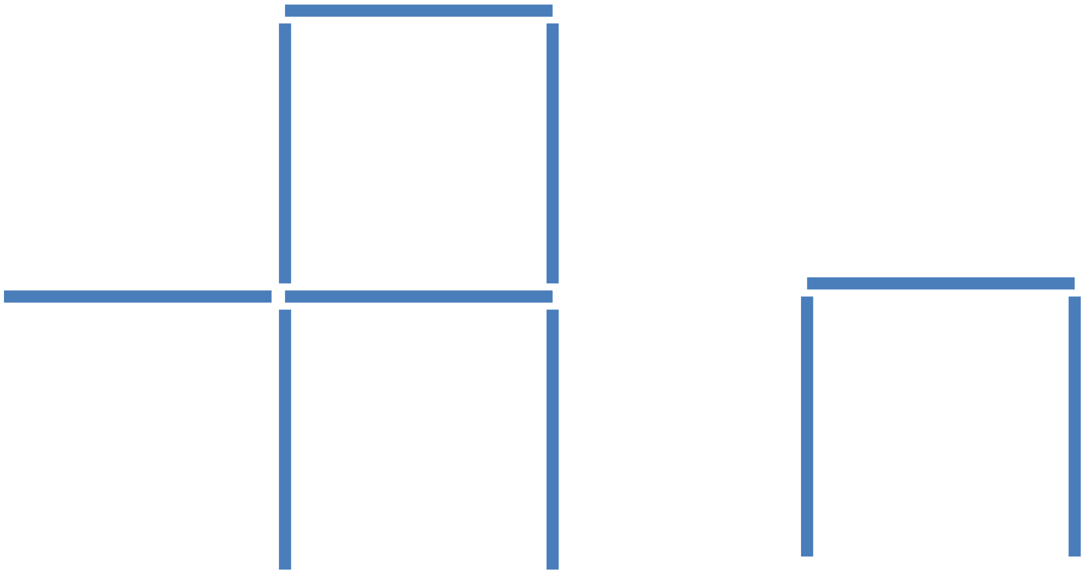
5.6 years old boy



5.6 years old girl

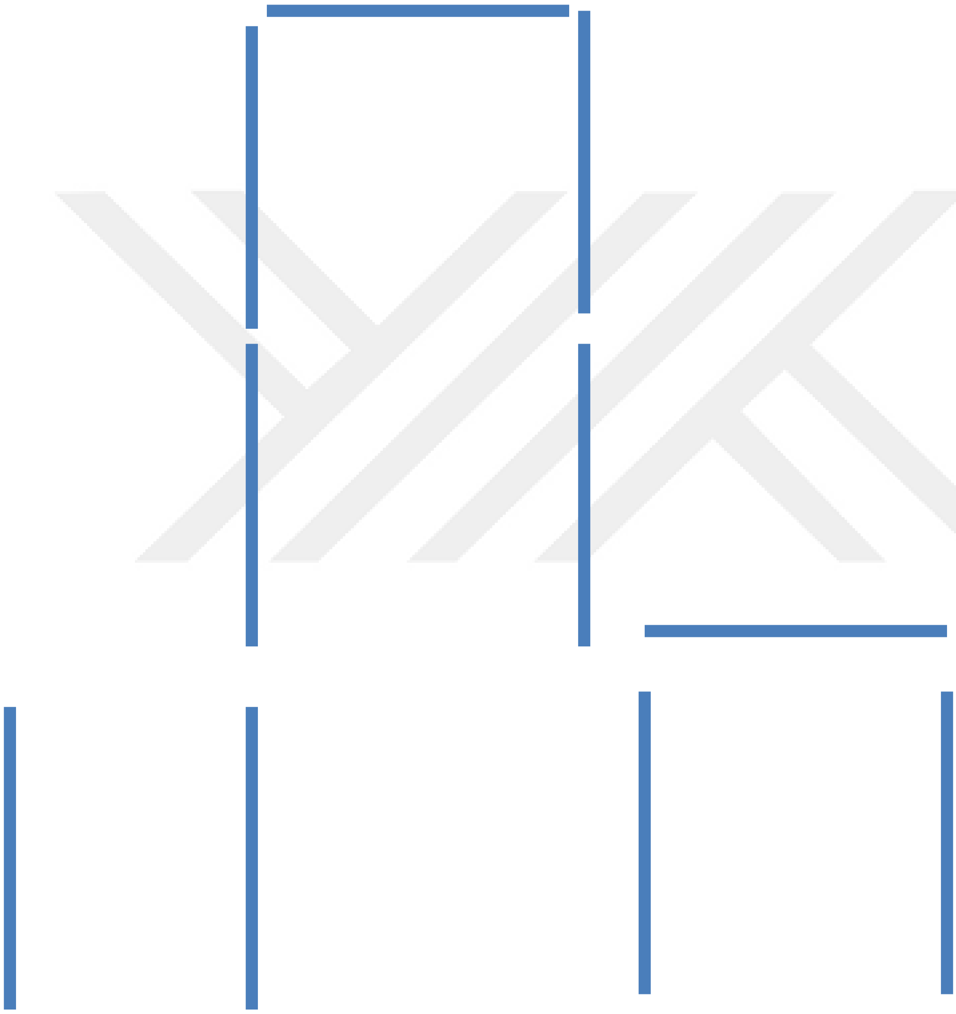


4.6 years old boy



5.8 years old boy

4.8 years old girl



Supplementary material 3

Results show that the difference between age groups in hierarchical complexity, $U = 316$, $z = 0.935$, $p = .35$, hierarchical resemblance, $U = 337$, $z = 1.398$, $p = .162$, and inhibition latency, $U = 204$, $z = -0.892$, $p = .372$, were not significant. However, tree structuring processing time, $t(35.42) = 3.348$, 95% CI [9.5, 38.76], $p = .002$, *Glass's delta* = .07, and standardized hierarchical complexity, $t(45) = -2.988$, 95% CI [-52.01, -10.12], $p = .006$, *Cohen's d* = .09, were significantly different between groups (See Table 7 for descriptive statistics). There was a significant positive two-tailed Spearman correlation between hierarchical complexity competence and hierarchical resemblance competence, $r_s = .57$, $p \leq 0001$. Inhibition latency was not significantly correlated with any of the hierarchical structuring measures ($p > .05$).

Table 7: Descriptive statistics of predictor tasks according to age groups

Variables	Age groups							
	3-to-4-year-old				5-to-6-year-old			
	n	*M*	*SE*	*Actual Range*	*n*	*M*	*SE*	*Actual Range*
Hierarchical complexity	26	56.31	3.87	30 – 86	21	65.67	5.79	34 – 123
Hierarchical resemblance	26	7.23	0.42	3 – 10	21	8.10	0.42	5 – 10
Tree structuring processing time	26	74.85	6.5	26 – 153	21	50.71	3.11	30 – 81
Hierarchical complexity (standardized)	26	57.31	6.1	15 – 145	21	88.38	8.71	34 – 162
Inhibition latency (in miliseconds)	22	1566	109	700 – 2836	22	1432	79	936 – 2432
Inhibition accuracy (number of correct responses)*	29	9.55	1.161	0 – 16	22	13.64	0.41	8 – 16

*This measure was not used in the analysis. Descriptive statistics of this measure are given for clarification. All the task errors were coded as zero.

Supplementary Material 4

Follow-up analysis with the full sample size

The following analysis were computed for the full sample size, although all the 5-to-6-year-old children got the higher score. Hierarchical complexity differed significantly between children who obtained low tool making scores (*n* = 9, *M* = 45.67) and who obtained high tool making scores (*n* = 37, *M* = 64.59), *t* (34.048) = -2.284, 95% CI [-35.633, -2.223], *p* = .001; however, hierarchical resemblance, *t*(44) = -1.37, *p* = .178 were not significantly different, and tree structuring processing time, *t*(44) = 2.006, *p* = .051, were marginally significantly different between these two groups. Also standardized hierarchical complexity between children who obtained low tool making scores (*n* = 9, *M* = 40.46) and who obtained high tool making scores (*n* = 17, *M* = 79.36) were significantly different, *t* (38.944) = -5.002, 95% CI [-54.63, -23.17], *p* ≤ .0001. Inhibition latency was significantly longer in the low tool making score group (*n* = 8, *M* = 1934) than in the high tool making score group (*n* = 35, *M* = 1409), *t* (8.349) = 2.493, 95% CI [42.834, 1008.068], *p* = .036.

APPENDIX B

SUPPLEMENTARY MATERIALS OF CHAPTER 4

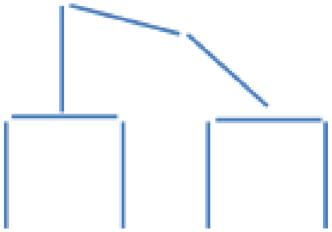
Supplementary material 1

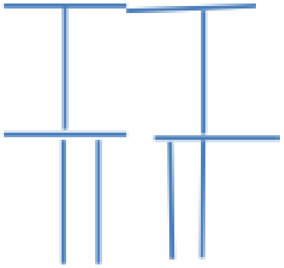
A pilot study for wooden sticks group and predictor tasks

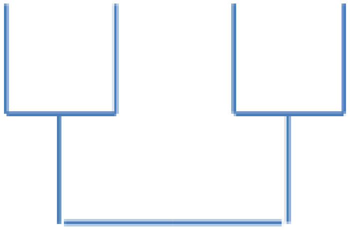
In order keep all the groups comparable, a pilot study was conducted with 7 additional children (5-6.5-years-old) before the main study, either with a warm-up phase or not. The reason for this pilot study was that the wooden sticks look perceptually more complex than the other tools (children were given two wooden pieces, the longer of which had two holes). Observational results revealed that children preferred to use only the long stick and their attention was not drawn to the holes or the small wooden piece. Therefore, children in the wooden sticks in the real study group were allowed a 30 second warm-up period, during which they explored the sticks. During the warm-up period, children were encouraged to touch both of the tools and asked to check their shapes. After the warm-up, the experimenter brought the tools back and introduced the tool innovation task. Some children had already combined the long and the short sticks in the pilot study during the warm-up and they just used the tool as-it-is in the main task. Consequently, the experimenter took the tools back before the task and gave them new (disassembled) sticks after introducing the task in the real study. Children were also given two predictor tasks in the pilot study (see the section titled ''Materials, experimental design and procedure''). Although hierarchical structuring task was relatively easy for these children, observational results indicated that the divergent thinking task (alternate uses task, Guilford et al., 1978; Runco, 1986) was challenging for 5-to-7-year-old children. Therefore, the experimenter prompted the children after each response and asked different versions of the same question (''can you please tell me, what can you do with it?'') to motivate thinking divergently in the real study (see ''*Divergent thinking task'' section* under ''Materials, experimental design and procedure'' section)

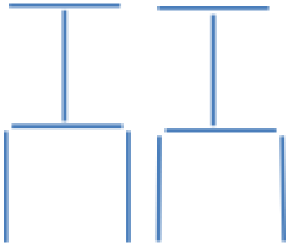
Supplementary material 2

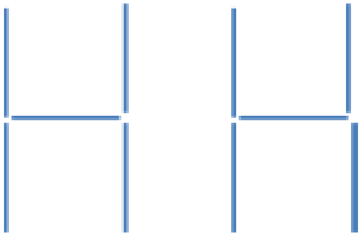
Hierarchical shapes made by children

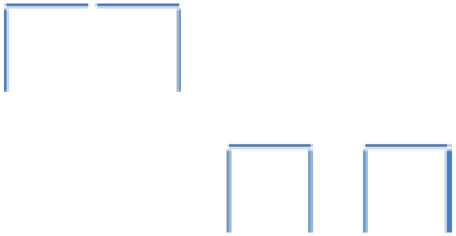












Supplementary material 3

Table 8: Comparisons of Different Link Functions in the First GLM-1

Model-1*

Distribution	Link function	Goodness of Fit			
		Bayesian Information Criterion (*BIC*)	Deviance		
			Value	*df*	*Value/df*
Multinomial	Cumulative Cauchit	204.453	141.243	180	0.785
Multinomial	**Cumulative complementary log-log**	**197.64**	**134.429**	**180**	**0.747**
Multinomial	Cumulative logit	200.164	136.953	180	0.761
Multinomial	Cumulative negative log-log	198.603	135.393	180	0.752
Multinomial	Cumulative probit	198.516	135.306	180	0.752

* Of the lowest two *BIC* scores listed, the one which has the lowest *devience value* is recommended in the literature to be used for the subsequent models. Dependent variable is the tool innovation scores. Frequency of each score (score 1, score 2, score 3, and score 4) is as follows: 10, 19, 26, and 19, respectively.

Supplementary Material 4

Table 9: Parameter estimates of the two GLM models with Multinomial distribution and cumulative complementary log-log link function. Interactions are indicated with 'X' and the effects are specified with letters (A, B, C, D). Except from the distribution type and link function of the dependent variable, the rest is the same (total number of the effects and the dependent variables) with the Model 1 above.

		B	*SE B*	*Wald* χ^2	*p*
Model 1*					
Treshold	[Tool making score=4]	-7.779	2.001	15.126	≤ .0001
	[Tool making score=3]	-6.396	2.008	10.152	.001
	[Tool making score=2]	-5.238	2.026	0.457	.01
Task type: WS	(A) PC vs WS	-5.704	1.243	21.048	≤ .0001
	(B) BS vs WS	-4.698	1.485	10	.002
Gender: girls	(C)	-1.042	0.566	3.389	.066
Task Type X Gender	A X C	1.316	0.702	3.516	.061
	B X C	-0.414	0.832	0.247	.619
Hierarchical Complexity	(D)	-0.062	0.015	17.069	≤ .0001
Hierarchical Complexity X Task type	A X D	0.056	0.015	14.547	≤ .0001
	B X D	0.048	0.018	6.903	.002
Age in months		-0.004	0.029	0.017	.897
(Scale)		1			
Model 2					
Treshold	[Tool making score=4]	-13.997	2.973	22.165	≤ .0001
	[Tool making score=3]	-11.876	2.601	20.846	≤ .0001
	[Tool making score=2]	-9.735	2.316	17.674	≤ .0001
Gender: girls		-1.904	0.683	7.754	.005

Hierarchical complexity		-0.081	0.02	15.920	≤ .0001
Divergent thinking		-0.677	0.196	11.871	.001
(Scale)		1			

APPENDIX C

SUPPLEMENTARY MATERIALS OF CHAPTER 5

Supplementary material 1

Examples for hierarchical action

In an experiment in which 1-to-3-year-old children are instructed to nest some cups (of various sizes), Greenfield, Nelson and Saltzman (1972) demonstrate that 3-year-old children use a method called the subassembly method, in which the cups are combined in a hierarchical fashion (e.g., nesting two cups and then putting them together inside a bigger cup), while the younger ones use simpler strategies such as the pairing strategy (e.g., putting a cup into a single static one). In the same task, chimpanzees sometimes use complex strategies, such as subassembly or pot method (putting various cups one by one into a static cup) (Matsuzawa, 1991), but capuchin monkeys mostly use the simplest method, namely the pairing strategy (Westergaard & Suomi, 1994).

Culture and the second study

Note that the task in this study does not require joint action for its solution. However, if joint interaction supports decision making processes about the task (Tomasello et al., 2005), then participants would form a shared representation of the task, and this shared representation would facilitate solving the tool making problem. Studies classify Turkey as a collectivist culture and New Zealand as an individualistic culture (see Oyserman et al., 2002). Culture-specific approaches to solving problems may lead to differential success of the dyads. This is because the effect of collaboration on innovation success may be two-fold: Collaboration may facilitate but sometimes even inhibit performance (for a review see Nokes-Malach, Richey, & Gadgil, 2015). Here, we wonder whether Turkish children raised in a more collectivistic culture may try to solve the hook task together, possibly inhibiting their individual performance and innovation results. On the other hand, New Zealand children raised in a more individualistic culture may focus on solving the problem individually, while their joint interaction may still provide a shared representation of the task.

Data analyses

The main reason why the GLM approach is used is that standard General Linear Models are very biased if the data is non-normally distributed, and the experimental group sizes are unequal (Agresti, 2015; Madsen & Thyregold, 2010). GLM was introduced by McCullagh and Nelder (1989), which allows identifying the type of distribution from the exponential family and a link function. GLM is therefore a very powerful method for analyzing non-normally distributed data (Madsen & Thyregold, 2010). Based on the previous studies' tool making score distribution, ordinal regression with complementary-log-log link function with GLM was calculated in order to find whether the predictors for the tool making scores – hierarchical complexity and divergent thinking (pencil or pipe cleaner) – were significant. As the sample sizes between groups were unequal, the *Fisher* scoring method was used for the parameter estimation. The robust estimator for the covariance matrix method was used, because of the sample size difference between groups and unequal percentages of tool making scores (see, Agresti, 2015). As the sample size of one group (total number of dyads in the joint group) was naturally half of the individual group, *likelihood ratio chi-square* statistics were calculated for the test of model effects rather than *Wald chi-square* statistics which is not recommended for small or unequal sample sizes (see, Agresti, 2015).

All significance levels were set to $p \leq .05$. Non-parametric tests were used if the data violated normality and/or homogeneity of variance assumptions in exploratory tests before the GLM model or as follow-up test after the main analysis. Effect sizes were given for significant results (e.g., phi – ϕ – for chi-squares, or r for non-parametric tests).

Supplementary material 2

Study 1: preparatory results and discussion

Results from tool-making scores showed that there was a significant difference between girls (Mdn = 16.83) and boys (Mdn = 24.26), $U = 132$, $z = -2.064$ $p = .039$, $r = .32$. Hierarchical complexity, $U = 158.5$, $z = -1.478$, $p = .139$, divergent thinking with the pipe cleaner, $t(37) = 0.187$, $p = .853$, and divergent thinking with the pencil, $U = 181$, $z = -0.161$, $p = .878$, were not significantly different between girls and boys. Results from predictor tasks demonstrated that hierarchical complexity, $U = 132$, $z = -1.81$, $p = .121$, divergent thinking with the pipe cleaner, $U = 219$, $z = 1.307$, $p = .206$, and divergent thinking with the pencil, $U = 208$, $z = 1.016$, $p = .331$ were not significantly different between individual and joint groups (See Table 10 for descriptive statistics). Predictor measures were not significantly correlated with each other: hierarchical complexity and divergent thinking with the pipe cleaner $r_s(39) = 071$, $p = .667$, hierarchical complexity and divergent thinking with the pencil, $r_s(39) = 104$, $p = .529$, and divergent thinking with pipe cleaner and the pencil, $r_s(39) = 236$, $p = .148$. See Table 10 for descriptive statistics of the predictors according to factors.

The gender difference in the tool-making scores with wooden sticks is compatible with the results of our previous study (see Chapter 4). However, when the pipe cleaner was used with the same task, there was no gender difference (Cutting et al., 2011). It should be noted that the gender difference is less striking in the joint group, which will be further explored in the second study. There may be two features underlying the gender difference in tool use. The first one might be experience related. Girls might be playing with familiar tools and toys as-they-are while boys tend to change the shape or manipulate tools or toys. In their study with older school children, Jones et al. (2000) showed that girls showed a greater tendency to follow the instructions of a tutor while using science tools, whereas boys were more explorative in their behavior. Secondly, it may be a cultural norm that caregivers motivate girls more than boys to keep the shape of the toys or tools. This might also have been one reason for why it was harder to find girls as participants for the present study than boys. Clarifying the reason(s) underlying our gender differences is beyond the scope of the current study, but would be interesting to explore in future work.

Table 10: Descriptive statistics of the dependent variable (tool making scores) and the predictors (covariates: hierarchical complexity, divergent thinking) according to factors used in Experiment 4.

Factors		Dependent variable and covariates	Descriptive Statistics			
			n	*M*	*SE*	*Actual Range*
Gender	Girls	Tool making scores	18	2.11	0.212	1 – 3
		Hierarchical complexity	18	70.08	4.419	38 – 86
		Divergent thinking	17	5.38	0.415	3 – 9
	Boys	Tool making scores	23	2.78	0.198	1 – 4
		Hierarchical complexity	23	77.54	3.31	34 – 86
		Divergent thinking familiar	22	5.42	0.401	1 – 9
Group	Individual	Tool making scores	27	2.37	0.208	1 – 4
		Hierarchical complexity	27	76.55	3.567	34 – 86
		Divergent thinking	25	5.08	0.374	1 – 9
	Joint	Tool making scores	14	2.71	0.194	1 – 4
		Hierarchical complexity	14	69.86	3.865	42 – 86
		Divergent thinking	14	5.98	0.405	3 – 9

Table 11: Parameter Estimates Table for Experiment 4. 95 % Profile Likelihood Confidence Intervals (CI) for B values are Shown in Brackets beneath the Values. The Factors are labeled in Terms of Its Comparison Level (e.g., Group: individual).

				Hypothesis Test		
		B	*SE*	*Wald*χ^2	*df*	*p*
Threshold	Tool making Score 4	-10.679 [-16.2, -6.56]	2.191	23.759	1	≤. 0001
	Tool making Score 3	-8.00 [-12.566, -4.461]	1.876	18.185	1	≤. 0001
	Tool making Score 2	-6.344 [-10.555, -3.124]	1.583	16.064	1	≤. 0001
Group: individual		-1.09 [-2.281, -0.01]	0.406	7.201	1	.007
Gender: boys		1.323 [0.393, 2.411]	0.426	9.646	1	.002
Hierarchical complexity		-0.066 [-0.109, -0.032]	0.016	17.27	1	≤. 0001
Divergent thinking (pipe cleaner)		-0.479 [-0.929, -0.094]	0.147	10.661	1	.001
Divergent thinking (pencil)		-0.626 [-1.16, -0.133]	0.196	10.197	1	.001
(Scale)		1				

Study 2: preparatory results and discussion

There was no significant difference in tool-making scores based on gender in the overall sample which combined the two joint groups, Turkish and New Zealand , *U* = 99, *z* = -0.530, *p* = .65. Turkish and New Zealand joint groups were compared on their results on the predictor tasks. New Zealand children, *Mdn* = 18.94, scored significantly higher on hierarchical complexity than did Turkish Children, *Mdn* = 11.57, (*U* = 30, *z* = 2.531, *p* = .022, *r* = .46). On the other hand, Turkish children scored significantly higher on divergent thinking with the pencil than did New Zealand children, *U* = 59.5, *z* = -2.045, *p* = .046. Divergent thinking with the pipe cleaner were not significantly different between two groups, *U* = 95, *z* = -0.451, *p* = .683. None of the predictors were significantly inter-correlated, with a maximum *p* value of .68 (see Supplementary Material Table 12 for descriptive statistics).

Results demonstrated that New Zealand children had higher hierarchical complexity scores. This might be explained by early schooling in New Zealand. While there is some literature on the effect of early schooling on executive function abilities on pre-school children (Brod, Bunge, & Shing, 2017) the effect of early schooling on different object manipulation tasks should be further investigated. On the other hand, divergent thinking results with the pencil were higher in the Turkish joint group. While the pipe cleaner is relatively novel tool for both cultures and flexible enough to make changes at hand, which might trigger divergent thinking, pencil is a functionally fixed tool. In the literature, it is known that familiar tools have more fixed functions, and the functional fixedness of the tool hinders innovative or creative problem solving (Hanus, Mendes, Tennie, & Call, 2011; Adamson, 1952). However, since Turkish children do not have early schooling, they might focus on pretend play as they have more time allocated to playing in kindergarten.

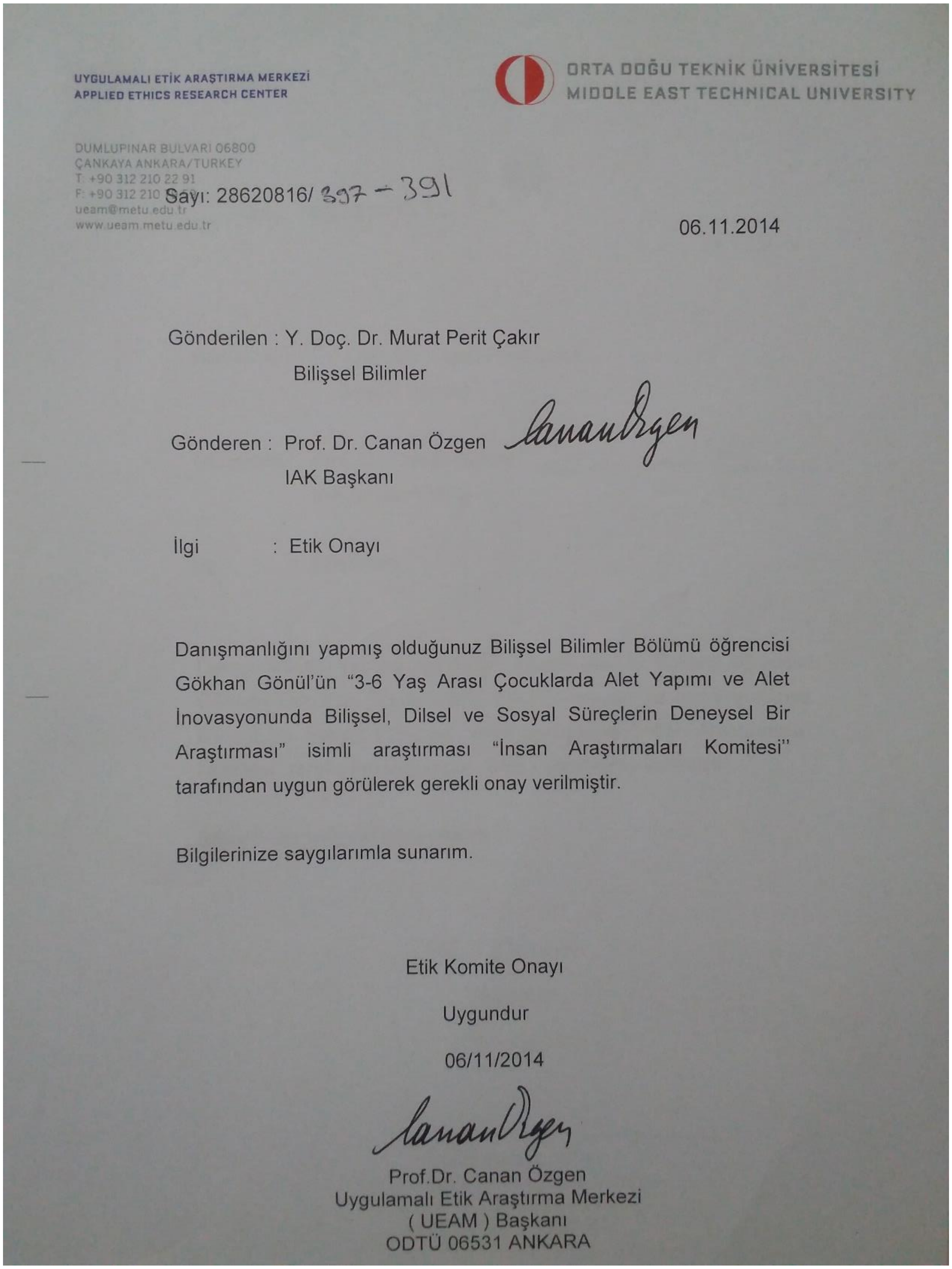
Table 12: Descriptive Statistics for the Experiment 5. Turkish and New Zealand Data is Compounded for the Gender Factor.

Factors		Dependent variable and covariates	Descriptive Statistics			
			N	*M*	*SE*	*Actual range*
Gender	Girls	Tool making scores	13	2.62	0.18	1 – 3
		Hierarchical complexity	13	63.17	3.91	42 – 86
		Divergent thinking	12	5.25	0.502	3 – 9
	Boys	Tool making scores	17	3.29	0.166	1 – 4
		Hierarchical complexity	17	80.79	2.48	33.5 – 86
		Divergent thinking	17	5.54	0.304	3 – 8
Group	Joint New Zealand	Tool making scores	16 dyads	3.25	0.171	1 – 4
		Hierarchical complexity	16 dyads	82.97	1.662	63 – 86
		Divergent thinking	15 dyads	4.90	0.313	3 – 7

APPENDIX D

LOCHAL ETHICAL COMMITTEE FORMS FOR STUDIES

Experiment 1, 3 and 4: Data collection from children in Turkey



UYGULAMALI ETİK ARAŞTIRMA MERKEZİ
APPLIED ETHICS RESEARCH CENTER

ORTA DOĞU TEKNİK ÜNİVERSİTESİ
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06.11.2014

Gönderilen : Y. Doç. Dr. Murat Perit Çakır
Bilişsel Bilimler

Gönderen : Prof. Dr. Canan Özgen Canan Özgen
IAK Başkanı

İlgi : Etik Onayı

Danışmanlığını yapmış olduğunuz Bilişsel Bilimler Bölümü öğrencisi Gökhan Gönül'ün "3-6 Yaş Arası Çocuklarda Alet Yapımı ve Alet İnovasyonunda Bilişsel, Dilsel ve Sosyal Süreçlerin Deneysel Bir Araştırması" isimli araştırması "İnsan Araştırmaları Komitesi'' tarafından uygun görülerek gerekli onay verilmiştir.

Bilgilerinize saygılarımla sunarım.

Etik Komite Onayı

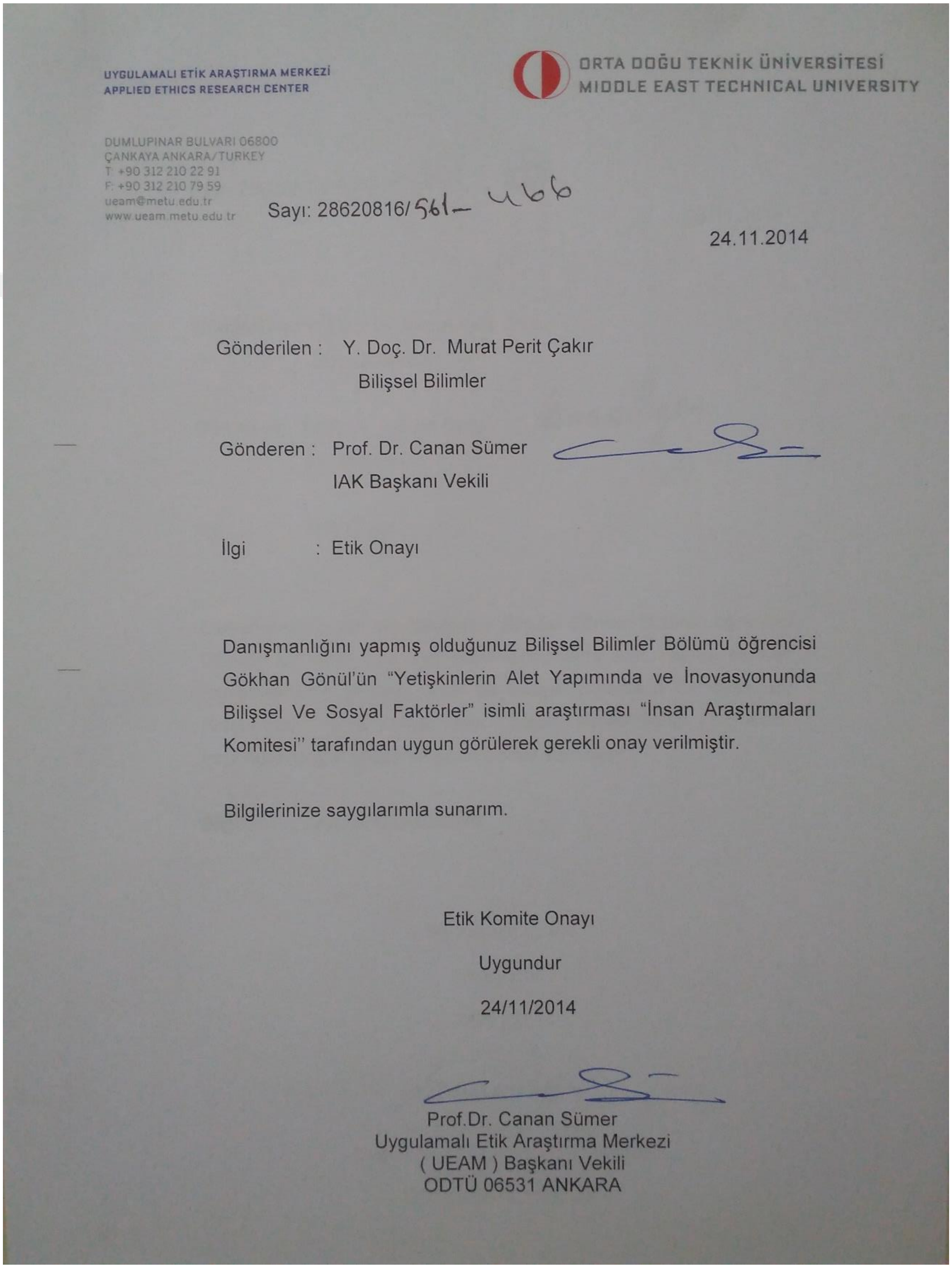
Uygundur

06/11/2014

Canan Özgen

Prof.Dr. Canan Özgen
Uygulamalı Etik Araştırma Merkezi
(UEAM) Başkanı
ODTÜ 06531 ANKARA

Experiment 2: Adult data collection



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Sayı: 28620816/561– 466

24.11.2014

Gönderilen : Y. Doç. Dr. Murat Perit Çakır
Bilişsel Bilimler

Gönderen : Prof. Dr. Canan Sümer
IAK Başkanı Vekili

İlgi : Etik Onayı

Danışmanlığını yapmış olduğunuz Bilişsel Bilimler Bölümü öğrencisi Gökhan Gönül'ün "Yetişkinlerin Alet Yapımında ve İnovasyonunda Bilişsel Ve Sosyal Faktörler" isimli araştırması "İnsan Araştırmaları Komitesi'' tarafından uygun görülerek gerekli onay verilmiştir.

Bilgilerinize saygılarımla sunarım.

Etik Komite Onayı

Uygundur

24/11/2014

Prof.Dr. Canan Sümer
Uygulamalı Etik Araştırma Merkezi
(UEAM) Başkanı Vekili
ODTÜ 06531 ANKARA

Experiment 5: Data collection from New Zealand children

Office of the Vice-Chancellor
Finance, Ehtics and Compliance

The University of Auckland
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Auckland, New Zealand

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Telephone: 64 9 373 7599
Extension: 87830 / 83761
Facsimile: 64 9 373 7432

UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE (UAHPEC)

21-Dec-2015

MEMORANDUM TO:

Dr Annette Henderson
Psychology

Re: Application for Ethics Approval (Our Ref. 016580): Approved with comment

The Committee considered your application for ethics approval for your project entitled **Joint tool making in pre-school children: From cognitive to social factors .**

Ethics approval was given for a period of three years with the following comment(s):

Please amend the following:

1. PISs
a. Please clarify that participants who withdraw or otherwise do not complete the study will still receive the koha.
b. Please use a University of Auckland email address for the PhD researcher, and not a personal email.

2. PISs and CFs
a. Please update any statements about withdrawing or stopping the session with the phrase "without giving a reason".

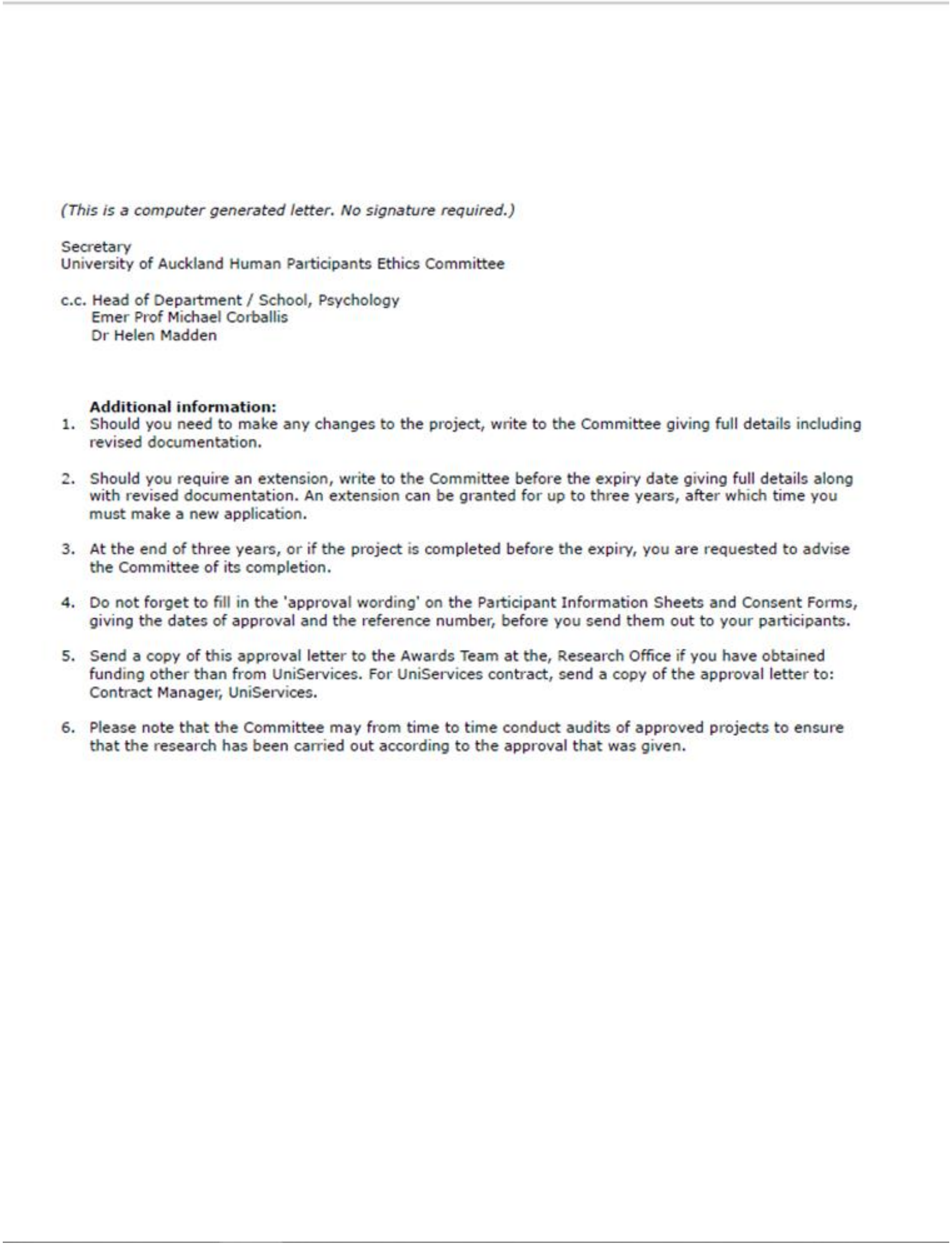
The expiry date for this approval is 21-Dec-2018.

If the project changes significantly you are required to resubmit a new application to UAHPEC for further consideration.

In order that an up-to-date record can be maintained, you are requested to notify UAHPEC once your project is completed.

The Chair and the members of UAHPEC would be happy to discuss general matters relating to ethics approvals if you wish to do so. Contact should be made through the UAHPEC Ethics Administrators at ro-ethics@auckland.ac.nz in the first instance.

All communication with the UAHPEC regarding this application should include this reference number: **016580.**



(This is a computer generated letter. No signature required.)

Secretary
University of Auckland Human Participants Ethics Committee

c.c. Head of Department / School, Psychology
Emer Prof Michael Corballis
Dr Helen Madden

Additional information:

1. Should you need to make any changes to the project, write to the Committee giving full details including revised documentation.
2. Should you require an extension, write to the Committee before the expiry date giving full details along with revised documentation. An extension can be granted for up to three years, after which time you must make a new application.
3. At the end of three years, or if the project is completed before the expiry, you are requested to advise the Committee of its completion.
4. Do not forget to fill in the 'approval wording' on the Participant Information Sheets and Consent Forms, giving the dates of approval and the reference number, before you send them out to your participants.
5. Send a copy of this approval letter to the Awards Team at the, Research Office if you have obtained funding other than from UniServices. For UniServices contract, send a copy of the approval letter to: Contract Manager, UniServices.
6. Please note that the Committee may from time to time conduct audits of approved projects to ensure that the research has been carried out according to the approval that was given.

CURRICULUM VITAE

Gökhan Gönül

Graduate School of Informatics, Cognitive Science Department, Middle East Technical University (METU)
Çankaya, 06800 Ankara, Turkey
E-mail: gokhan.gonul@metu.edu.tr

Date & Place of Birth: 13.03.1986, Muğla/Turkey

EDUCATION:

- **01 October 2018 – 31 July 2019**: Post-Doctoral Researcher in Ludwig Maximilians University - Faculty of Psychology and Educational Sciences
- **01 November 2015 – 20 June 2016:** Visiting Doctorate Researcher in University of Auckland - School of Psychology
- **15 May 2014 Passed Ph.D. qualifying exam**
- **2013 Accepted as Ph.D. student** in Cognitive Science, Middle East Technical University, Ankara, Turkey
- **2010 – 2013 M.Sc. student** in Cognitive Science, Middle East Technical University, Ankara, Turkey
- **2007 – 2010 B.Sc. student** in Sociology, Uludağ University, Bursa, Turkey
- **2005 – 2010 B.Sc. student** in Psychology, Uludağ University, Bursa, Turkey

PAPERS:

- **Gönül, G.**, Takmaz, E., Hohenberger, A., & Corballis, M. (**2018**). The cognitive ontogeny of tool making in Children: The role of inhibition and hierarchical structuring. *Journal of Experimental Child Psychology*, 173, 222-238. https://doi.org/10.1016/j.jecp.2018.03.017
- **Gönül, G.**, Hohenberger, A., Corballis, M., & Henderson, A. (**under revision**). Joint and individual tool making in preschoolers: from social to cognitive processes.

- **Gönül, G.**, Takmaz, E., Hohenberger, A., & Corballis, M. (**in preparation**). Ontogeny of tool making in children: perceptual-action and representational factors

- **Gönül, G.** & Zeyrek, D. (**2014**). Discourse connectives and lexical cohesion: An experimental investigation of sentence processing in Turkish. *Proceedings of the 36th Annual Conference of the Cognitive Science Society* (pp. 2281-2287). Quebec City, Canada: Cognitive Science Society. https://mindmodeling.org/cogsci2014/papers/397/paper397.pdf

ACHIEVEMENTS and SUMMER/SPRING SCHOOLS:

- **Research Grant:** DAAD Research Grants for Doctoral Candidates and Young Academics and Scientists (57381410)

- **Scholarship:** Graduate Scholarship by Council of Higher Education, Turkey, Faculty Development Program (**Salary and project support** through MSc and PhD)

- **Summer School Participation and Grant:** The Initiative for a Synthesis in Studies of Awareness Summer School, 22 May – 5 June 2017, Osaka, Japan (**Granted by** The Okinawa Institute of Science and Technology, travel and accommodation expenses)

- **Conference Travel Grant:** International Convention of Psychological Science (ICPS), 23 – 25 March 2017, Vienna, Austria (**Granted by** Association for Psychological Science, 700 $)

- **Spring School Participation and Grant:** Spring School: Social Cognition, Emotion and Joint Action, 6 – 10 March 2017, Bochum, Germany (**Granted by** Ruhr-Universität, 250 €)

- **Project Grant:** Visiting Doctorate Researcher in University of Auckland - School of Psychology (**Funded by** The Scientific and Technological Research Council of Turkey; TUBİTAK-2214-A, 2015-1, 1059B141500520, 14.400 $ + travel expenses)
    - **Project Name:** Joint tool making in 5-6 years of children: From cognitive to social factors
    - **Project Advisors:** Prof. Dr. Michael Corballis, Dr. Annette Henderson

- **Summer School Participation and Grant:** Amsterdam Brain and Cognition Summer School 2014: From genes to Cognition, Netherland: Amsterdam (**Funded by** The Scientific and Technological Research Council of Turkey, 1500$)

- **Summer School** 21st International Summer School in Cognitive Science, 30 June – 11 July, 2014, Sofia, Bulgaria

MEMBERSHIP:

Association for Psychological Science (Member Number: 148866)

Cognitive Science Society (Member Number: 0007548)

WORK EXPERIENCE:

2011- ongoing Research and Teaching Assistant: Middle East Technical University, Graduate School of Informatics, Department of Cognitive Science

Assisted with the following courses:

- Cognitive Development
- Language and Cognition
- Language Acquisition
- Human Memory
- Visual Cognition
- Topics, Research Methods and Ethics in Cognitive Science
- Research Methods and Statistics for Cognitive Science
- Cognition, Perception & Action
- Psychology of Reading
- Cognitive Semantics

PROJECTS:

- **Project assistant (Ongoing project).** Insight or Social Learning? The Effect of Napping and Task Breaking on the Innovative Problem Solving Ability of Children (Middle East Technical University Scientific Investigation Project**,** 2700**; Project Group: Gökhan Gönül, Assoc. Prof. Annette Hohenberger, Assist. Prof. Dr. Murat Perit Çakır, Anıl Karabulut)**

- **Project Assistant (Completed project):** An Experimental Investigation of Cognitive, Language and Social Processes in Tool Making and Tool Innovation in Children (Middle East Technical University Scientific Investigation Project, BAP-07-04-2015-001; **Project Manager: Assoc. Prof. Annette Hohenberger**)

- **Project Assistant (Completed project):** Effects of Post-traumatic Stress Disorder on the Eye Movement Patterns: An Experimental Investigation with Analysis of eye Movements (Middle East Technical University Scientific Investigation Project, BAP-08-11-2013-003; **Project Manager: Assist. Prof. Cengiz Acartürk**)

- **Project Assistant (Completed project):** Inter-language Discourse Structure and Enriching Turkish Discourse Bank (Middle East Technical University Scientific Investigation Project, BAP-07-04-2014-005; **Project Manager: Prof. Dr. Deniz Zeyrek**)

POSTER PRESENTATIONS:

- Gönül, G., Hohenberger, A., Corballis, M. & Henderson, A. (4-5 January/2018). The ontogeny of tool innovation: Cognitive, social and cultural processes. *Budapest Central European University Conference on Cognitive Development (BCCCD18),* Budapest, Hungary.

- Gönül, G., Hohenberger, A., Henderson, A. & Corballis, M. (23-25 March/2017). Emergence of tool innovation in individual and dyadic contexts: Comparing Turkish and New Zealand preschool children. *International Convention of Psychological Science*, Vienna, Austria.

- Gönül, G., Hohenberger, A., Henderson, A. & Corballis, M. (6-10 March/2017). The ontogeny of tool-making in dyadic settings: Cultural, cognitive, and social processes in Turkish and New Zealand preschoolers. *Spring School: Social Cognition, Emotion and Joint Action,* Bochum, Germany.

- Gönül, G., Hohenberger, A. & Takmaz, E. (2016). Tool innovation in 5-6-year-old Turkish pre-school children: The effect of familiarity and salience of affordances. *24th Biennial Meeting of the International Society for the Study of Behavioural Development,* Vilnius, Lithuania.

- Gönül, G. & Hohenberger, A. (2015). Predicting the tool innovation ability of children: Hierarchical object manipulation and executive functioning. *17th European Conference on Developmental Psychology,* Braga, Portugal.

- Gönül, G. & Hohenberger, A. (2015). Tool making and object manipulation in children: Cognitive Factors. *2nd International Symposium on Brain and Cognitive Science, Middle East Technical University,* Ankara, Turkey.

- Gönül, G. & Hohenberger, A. (2015). The role of hierarchical structuring and executive functioning in tool innovation processes of pre-school children. *The Nature and Origins of Human Cognition Conference.* Berlin, Germany.

- Gönül, G. & Hohenberger, A. (2015). Individual and joint tool making in preschoolers: from cognitive to social processes. *9th Annual Conference on the Evolutionary Behavioral Sciences.* Boston, USA.

RESEARCH INTERESTS:

- Evolution and development of cognition (ongoing research program)
    - Development of tool making and innovation ability
    - Joint interaction and the evolution of tool making
- Development of social cognition
- Language comprehension