A new perspective on technology-driven creativity enhancement in the Fourth Industrial Revolution

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Abstract

Technology is generally assumed to complement workers performing creative tasks by enhancing their ability to gather, store, share and transform knowledge. We advance an alternative view by conceptualizing how technology complements workers also by extending the domain, namely the set of symbolic and material elements underlying a given creative task. We elucidate the ways in which a domain extension complements workers' individual components of creativity, namely domain-relevant skills, creativity-relevant processes and task motivation. Furthermore, we underline the importance of renewing heuristics to reap the creativity-enhancing potential of the domain extension, as well as the role of the organizational context in this regard. Finally, we provide an illustrative example of our framework, referring to the adoption of additive manufacturing in Luxottica.

1. Introduction

Understanding to what extent and in what circumstances technology complements or substitutes for work is a widely investigated research problem. While technology decreases the value of some work by performing it in place of humans (substitution effect), it increases the value of other work by making it more productive (complementarity effect), with significant social consequences (Baldwin, 2019). Technology has traditionally been seen as substitute for low-skill work and a complement for high-skill work (Berman et al., 1994; Autor et al., 1998; Bresnahan et al., 2002). However, since the beginning of the new millennium, the debate has shifted from a skill-based to a task-based perspective. Automation and computerization have been suggested to substitute for routine manual and cognitive tasks, complementing non-routine cognitive tasks in particular (Autor et al., 2003).

Recently, the advent of the so-called Fourth Industrial Revolution (EPO, 2017; OECD, 2017) has reinvigorated the debate. Machines are becoming surprisingly capable in domains that were thought to be exclusively human, such as caregiving and complex communication, as the therapeutic pet Paro and Lionbridge’s Geofluent translation engine show (Brynjolfsson and McAfee, 2011, Baldwin, 2019). Artificial intelligence (AI) has even progressed to the point of mastering the most complex strategic games and creating novel artworks of human-level quality. Many studies have inquired into the susceptibility of jobs to these advanced forms of automation, with estimates of the percentage of jobs at risk of disappearing ranging from 47% (Frey and Osborne, 2017) to 33% (Pajarinen and Rouvinen, 2014) and 9% (Arntz, Gregory and Zierahn, 2017), depending on the country and the methodology adopted. These concerns have relatively overshadowed the other side of the coin: complementarity. Alongside new dynamics of substitution between machines and workers performing non-routine cognitive tasks, we argue that new dynamics of complementarity are also likely to emerge and rise in importance. We contribute to filling this gap by focusing on creative tasks, a subset of non-routine cognitive tasks that is considered vital for firms' survival and success (Cummings and Oldham, 1997) and expected to become increasingly relevant as technology advances further (World Economic Forum, 2018).

We refer to complementarity as the property of a relationship between two entities that enhance the value of each other. In firm contexts, value enhancement translates into an increase in the quantity and/or quality of output produced. However, determining the exact channels through which this happens is not immediate. In task-based approaches, automation and computerization have been proposed to complement workers performing non-routine cognitive tasks mainly through efficiency-related channels, by saving time, reallocating labor and providing higher quality inputs (Autor et al., 2003; Levy and Murnane, 2013). Zooming on creative tasks, scholars have focused on the idea that technologies may facilitate various stages of the creative process, such as information finding, idea finding and solution finding (Wang and Nickerson, 2017). They do so by helping workers to gather, visualize, circulate and transform knowledge (Siau, 1995; Dewett, 2003; Lubart, 2005), also thanks to creativity support tools like word processors, computer-aided design software, generative design software and computational engines (Shneiderman, 2002, 2007).

While these are certainly relevant complementarity channels, the impact of technology on creativity can be more holistic and pervasive. In particular, recent technological developments dramatically extend the feasibility frontier through advanced automation and digital-physical integration. Thus, they change the rules of the game by altering the domain where the creative activity takes place, enriching it with new symbols, techniques, procedures and understandings. By doing so, they provide employees with new building blocks to form creative solutions, thus complementing their creative capabilities. The higher the creativity of employees, the higher the benefit of domain-extending technologies on creative tasks; the higher the domain-extending potential of a new technology, the higher the value of having creative individuals ready to embrace it. Accordingly, we aim to develop a new domain-centered perspective on technology-driven creativity enhancement.

By adapting the systems model of creativity (Csikszentmihalyi, 1996), we argue that new technologies may complement workers performing creative tasks through a domain extension. We elucidate in detail how each component of the creative potential of the worker, consisting of domain-relevant skills, creativity-relevant processes and task motivation (Amabile 1983, 1988; Amabile and Pratt, 2016), contributes to the exploitation of the domain extension for creative purposes. Furthermore, we propose a dynamic mechanism whereby the organization itself may contribute to these multichannel complementarities, by helping workers develop new heuristics tailored to the extended domain. Finally, we illustrate how the proposed dynamics unfold in practice in the case of additive manufacturing (AM), one of the enabling technologies of the Fourth Industrial Revolution, and we present a case on AM extending the domain of designers in Luxottica, the global leader in the production of high-end eyewear.

This way, we aim to contribute both to the literature dealing with the relationship between technology and work, and to the more specific area of technology-driven creativity enhancement. Specifically, we contribute to the former by pinpointing an additional way whereby new technologies, especially those linked with the Fourth Industrial Revolution, may complement non-routine cognitive tasks involving creativity. We contribute to the latter by opening a new domain-driven perspective on technology-driven creativity enhancement, alongside the consolidated process-oriented stream dealing with circulation of knowledge, communication and creativity support tools. Several practical implications stem from this conceptual endeavor, related to the role of managers in smoothing the transition to the new domain, renewing the heuristics of employees and ensuring their diffusion within the organization.

The remainder of the paper is organized as follows. Section 2 reviews the literature on the relationship between technology and non-routine cognitive tasks. Subsection 2.1 refers to non-routine cognitive tasks in general, while Subsection 2.2 specifically focuses on creative tasks. As creative tasks are a subset of non-routine cognitive tasks, the two Subsections are closely related, and many complementarity channels that apply to the latter also implicitly apply to the former. Section 3 develops our conceptual framework, building on the systems model and the componential theory of creativity. Section 4 presents an empirical illustration of our framework, referring to the adoption of AM in Luxottica. Section 5 concludes, sketching some managerial implications and avenues for future research.

2. Literature review

2.1. Technology and non-routine cognitive tasks

The relationship between technology and work is a vibrant research area. Relevant theoretical developments stem from the observation of an historical pattern in the labor market: starting from the 1980s, middle-skill workers have lost ground to both high-skill and low-skill workers in many countries (Goos and Manning, 2007; Autor et al., 2008; Goos et al., 2009; Adermon and Gustavsson, 2015). Skill-biased technological change (SBTC) (Berman et al., 1994; Autor et al., 1998; Bresnahan et al., 2002) and subsequently routine-biased technological change (RBTC) (Goos et al., 2009, 2014) have been proposed to explain the aforementioned evidence.

In analyzing the technological impact on employment and wages, SBTC categorizes workers based on their skill, with skill generally denoting the level of education attained. On this premise, it proposes that technology complements high-skill workers and substitutes for low-skill ones. The underlying rationale is that while machines tend to be more efficient than humans in performing simple functions, they cannot replace the deep expertise and high-level analytical abilities of educated workers. Instead, educated workers are required to program, supervise and exploit machines fully, thus complementing them. Despite being appealing at first sight, this perspective overlooks the multitude of exceptions to the rule. Tasks like caring for the elders and entertaining children do not require a high level of education, but they are still hardly substitutable. To account for this, RBTC focuses on the nature of the task to be substituted, rather than the level of skill required. Accordingly, it proposes that the key determinant of substitutability is the extent to which a task is codifiable and repetitive. Thanks to its ability to perform well-defined instructions, technology substitutes for workers performing routine tasks, and complements workers performing non-routine ones (Autor et al., 2003).

Besides shifting the focus from skills to tasks, Autor and colleagues (2003) have also provided a taxonomy intersecting two dimensions to form four self-explanatory categories of tasks: routine manual tasks (e.g. assembly), non-routine manual tasks (e.g. caregiving), routine cognitive tasks (e.g. secretariat) and non-routine cognitive tasks (e.g. scientific research). Although more complex taxonomies have emerged over the years (e.g. Koorn, 2018), this quadripartite categorization is still the most widely adopted in studies on the relationship between technology and work, at multiple levels of analysis (e.g. Acemoglu and Autor, 2011; Frey and Osborne, 2017; Jaimovich and Siu, 2020). According to Autor and colleagues (2003), while the technology-driven substitution of routine-manual tasks has been possible since at least the industrial revolution, computerization has brought novelty in the form of symbolic processing. By virtue of their ability to process symbols, computers can store, manipulate and transfer information, thus being able to substitute for routine-cognitive tasks like those performed by clerks, telephone operators and bookkeepers. Conversely, non-routine manual and cognitive tasks remain outside the spectrum of substitutability.

However, recent technological advancements brought by the Fourth Industrial Revolution (EPO, 2017; OECD, 2017) are dramatically widening this spectrum. Robots are improving their environmental adaptation and interaction capabilities, thus being able to automate a wider range of non-routine manual tasks (e.g. drones for good delivery and therapeutic robots for caregiving). More strikingly, even the non-automatability of non-routine cognitive tasks is being called into question. AI spreads both fear and excitement due to its potential to supplant humans in non-routine cognitive tasks, by overcoming Polanyi's paradox (Autor, 2014). The combination of data availability, computational power and sophisticated machine learning algorithms allows machines to learn how to carry out tasks with high analytical complexity, through statistical inference. For example, machines have largely surpassed the ability of the best chess players in the world. Furthermore, they are now able to generate novel artworks and musical pieces that are almost indistinguishable from those created by a human expert. The realization that machines may have an edge over humans even in non-routine cognitive tasks has prompted a number of studies on the susceptibility of jobs to the so-called intelligent automation (Pajarinen and Rouvinen, 2014; Arntz et al., 2017; Frey and Osborne, 2017), with varying extent of pessimism.

While the new dynamics of substitution triggered by recent technological advancements are widely acknowledged and feared, new dynamics of complementarity are also likely to emerge, but they are much less investigated. According to Autor and colleagues (2003), computerization complements workers performing non-routine cognitive tasks through three channels. First, by automating routine tasks, they augment the share of labor devoted to non-routine cognitive tasks. Second, assuming an improvement, they may increase the productivity of workers performing non-routine cognitive tasks that use the output of automated tasks as an input (e.g. more accurate and comprehensive information improves managerial decision-making). This may happen not only sequentially, but also concurrently, as in the case of a surgeon watching continuous x-ray images on a screen while operating (Levy and Murnane, 2013). Third, they make the skills involved in non-routine cognitive tasks (e.g. problem-solving) more valuable, due to the comparative advantage of human labor. For related reasons, Acemoglu and Restrepo (2018) also add that technological advancement is likely to generate entirely new non-routine cognitive tasks, like those performed by big data analysts and audio-visual specialists.

These basic complementarity channels are still applicable in the context of advanced automation technologies. For example, by accelerating the production of prototypes, tools and spare parts, AM favors the allocation of time and energy on non-routine cognitive tasks like design. Natural language processing, a popular application of AI, enables advanced forms of text mining complementing the non-routine cognitive task of text interpretation. The emergence of cyber-physical systems makes the non-routine cognitive tasks of system supervision and problem solving more valuable (at least insofar as humans retain their comparative advantage vis-à-vis AI). However, new channels of complementarity linking new technologies with non-routine cognitive tasks have not been explored and conceptualized yet. In this regard, we propose that the presence of creativity in the characterization of a non-routine cognitive task implies several unexplored complementarity channels with technology. Such channels are becoming quite relevant as creative tasks grow in importance as the Fourth Industrial Revolution unfolds (World Economic Forum, 2018).

2.2. Technology and creative tasks

Creativity is commonly identified with the production of novel and effective ideas (Runco and Jaeger, 2012). Being a prominent antecedent of innovation, it is widely studied in management and organization theory at multiple levels of analysis (Anderson et al., 2014), ranging from the individual to the team and the whole firm (Woodman et al., 1993). The “creative task” expression is often used intuitively to denote a circumscribed instantiation of creativity (e.g. Carmeli et al., 2010; Harvey and Kou, 2013). Based on literature and interview data, Koorn et al. (2018) have endeavored to provide an explicit definition of creative tasks as “developing new meaningful ideas/artifacts”, and indeed it does not deviate much from the standard definition of creativity provided above. We too consider creative tasks as a subset of non-routine cognitive tasks almost entirely defined by the notion of creativity. Accordingly, they can be analyzed through the lenses provided by the vast corpus of studies on the cognitive, psychological, sociocultural and structural antecedents of creativity (Amabile, 1983, 1988; Guilford, 1984; Woodman et al., 1993; Csikszentmihalyi, 1996; Cropley, 2006; Simonton, 2015; Amabile and Pratt, 2016; Glăveanu, 2020). However, while creativity is typically introduced and analyzed as a microfoundation for innovation (Ford, 1996), we define creative tasks as an instantiation of creativity involving the exact same processes (e.g. convergent and divergent thinking), but without necessarily leading to innovation stricto sensu[1].

Extant literature offers a few preliminary insights on the impact of technology on creativity (and, in turn, creative tasks). First, at the highest level of abstraction, technologies are material objects. Materiality has a key role in the generation of creative ideas from a sociocultural perspective. Most notably, the recent perspective-affordance sociocultural theory of creativity (Glăveanu, 2020) frames material objects as dynamic embodiments of limits and possibilities. The available range of creative solutions stems from the complex interaction between individuals (with their history and experience) and objects, mediated by the sociocultural context. Tanggaard et al. (2016) offer a simple yet powerful illustration of this principle, by showing how the material of the ball actively contributes to the creative strategies enacted by elite players in handball matches. An important implication of this perspective is that the capability of interacting freely with material objects, going beyond functional fixedness to frame them in multiple unconventional ways, becomes an essential aspect of creativity.

In the more specific realm of technology, Dewett (2003) has elucidated how information and communication technology may engender a chain of creativity-enhancing effects within organizations, by facilitating knowledge absorption and codification, and enabling employees to communicate more easily and frequently. These benefits can be systematized and achieved through ad-hoc ensembles of tools, software and interfaces (Brennan and Dooley, 2005). A paradigmatic inter-employee communication enabler is the virtual team, with its peculiar set of dynamics and tools

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[1] The conception of new shapes for a logo or the graphics of a website are two examples of tasks that are creative in nature but can hardly be linked to the common interpretation of innovation.

(Chamakiotis et al., 2013). Among such tools, electronic brainstorming has been shown to increase group creativity with respect to verbal brainstorming, exemplifying the creativity-amplifying potential of technology in collaborative contexts (Siau, 1995). It is worth noting that indirect effects may also be present, as shown by suggestion system technologies, which enhance the creativity of employees by increasing their motivation (Fairbank and Williams, 2001).

At the individual level, generic computerization has the benefit of supporting the manipulation and storage of ideas, providing tutorials and databases, and offering insightful elaborations at various stages of the creative process (Lubart, 2005). A variety of technological artifacts ranging from search to visualization, simulation and mathematical manipulation tools have been conceptualized as "creativity support tools", an expression evoking their ability to bolster the creative potential of the user (Shneiderman, 2002, 2007). An example of a versatile and widespread creativity support tool is the Google search engine, which facilitates retrieval of information, an essential input for most creative endeavors. Instead, examples of domain-specific creativity support tools are computer-aided design software (Bonnardel and Zenasni, 2010) and the computational engine Wolfram Alpha. Such tools may help workers in various stages of the creative process, including information finding, idea finding and solution finding (Wang and Nickerson, 2017).

These contributions are all grounded in input or process perspectives. They clarify that technology may facilitate the retrieval, circulation and elaboration of knowledge at organizational, group and individual levels. Thus, creativity support tools and analogous mechanisms can be regarded as applications of the input-process complementarity channel between workers and non-routine cognitive tasks (Autor et al., 2003; Levy and Murnane, 2013) to the subset of creative tasks. However, we argue that the complementarity between technology and workers performing creative tasks goes beyond the ability of the former to improve creativity-relevant inputs or facilitate creative processes. By blurring the line between digital and physical domains, recent technological advancements challenge the feasibility frontier. Thus, they question workers' interpretation of what is feasible and what is not. We advance that this domain-centered perspective implies new complementarity channels between technologies and workers performing creative tasks, which we aim to conceptualize in the following Section.

3. A conceptual framework of domain-driven complementarity

The overarching structure for our conceptual framework lies in a readaptation of the systems model of creativity (Csikszentmihalyi, 1996). The systems model focuses on the genesis of “creativity with a capital C”, denoting extraordinary creative efforts that revolutionize one or more aspects of culture. On this premise, it argues that creativity stems from the complex and iterative interactions between the domain, the field and the individual. The domain is the architecture of symbolic rules and procedures characterizing each sphere (e.g. mathematics) and sub-sphere (e.g. algebra) of human knowledge. The individual is the creative person using the tools provided by the domain to introduce variation in the domain itself, or create a new domain entirely (e.g. the French mathematician Évariste Galois paving the way for the (sub)domain of Galois theory). The field is the ensemble of experts acting as gatekeepers in a given domain, thus selecting acceptable variations (e.g. the scientific community).

“Creativity with a capital C” is distinct from the standard notion of creativity (Runco and Jaeger, 2012), which is in turn slightly different from our definition of creative tasks. Furthermore, the broad context the systems model traditionally refers to is distinct from the organizational context we are analyzing. However, we argue that the tripartite conceptualization of domain, individual and field is still applicable and functional for the aims of the present work, after a slight adaptation. More specifically, given the economic orientation of firm settings, our notion of domain does not only cover symbolic elements, but also material tools and techniques. Furthermore, given the circumscribed scope of creative tasks, the individual does not necessarily introduce a sizeable variation in the domain[2]. Finally, firm settings require a wider interpretation of the field. In a sense, the market itself (i.e. consumers) may be considered the final gatekeeper, but on the other hand workers operate in an organizational context filtering market signals through its own sociocultural structure. In the light of this, some works in management and organization theory have recognized the presence of multiple overlapping fields (e.g. Ford, 1996). For the sake of simplicity, we identify the field with the organization where the creative task takes place, on the grounds that it represents the most direct influence on the performer of the task, integrating market signals with its corporate vision and sociocultural norms.

Given that creative tasks are performed by individuals, or groups that can be assumed to behave as individuals (Amabile, 1988), a characterization of the creative individual is also needed. A well-established taxonomy of the individual components of creativity recognizes domain-relevant skills, creativity-relevant processes and task motivation (Amabile, 1983, 1988, Amabile and Pratt, 2016). Domain-relevant skills refer to the mastery of a given domain through the accumulation of technical knowledge, practical expertise and talent. Creativity-relevant processes denote cognitive and psychological traits facilitating the generation of creative output (e.g. thinking outside the box, independence and healthy risk-taking behavior). Task motivation captures the motivational drivers of creative endeavors. Creativity typically requires intrinsic motivation, rooted in genuine passion, enjoyment and interest in the activity performed. Although extrinsic motivators like coercion and monetary rewards are negatively correlated with creative effort, synergistic extrinsic motivators like symbolic rewards and public displays of appreciation have been proposed, and to some extent shown, to increase creativity in tandem with intrinsic motivators (Amabile and Pratt, 2016).

The productivity of workers performing creative tasks may be measured as any combination of the quantity, quality and novelty of the output produced, with different weights depending on contextual

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[2] For example, although a new product design may be used as an inspiration by future designers (thus entering the domain lato sensu), it can hardly be regarded as a cultural revolution in the sense Csikszentmihalyi (1996) had in mind.

priorities. In any case, we posit it as a field-mediated function of the interaction between the characterization of the creative potential of the individual (as taxonomized above) and the state of the domain associated to the creative task. We define the state of a domain at any point in time as a well-specified set of symbolic and material elements including pieces of knowledge, tools and procedures relevant for performing the creative task. Consequently, domain-relevant skills determine the subspace of the domain (hereafter subdomain) spanned by the individual. Creativity-relevant processes determine the ability of the individual to explore different combinations of elements and recombine them in novel ways, potentially drawing from other subdomains as well. Intrinsic and synergistic extrinsic task motivation conjointly determine the propensity to do so, thus enhancing or depressing the application of creativity-relevant processes. The field (i.e. the organization) influences the interaction between the individual and the domain through high-level constructs like organizational culture and climate (Tesluk et al., 1997), also steering the extent and direction of creative efforts through managerial levers like feedbacks (Zhou, 2008) and goals (Litchfield, 2008).

Extant literature already recognizes that technologies may support domain-relevant skills (e.g. through enhanced search capabilities) and creativity-relevant processes (e.g. through enhanced visualization). However, we argue that the introduction of a new technology may also complement workers by changing the state of the domain. By providing new methods to transform inputs into outputs and procedures to retrieve, exchange and interpret data, possibly leading to novel understandings, a new technology may trigger a domain extension. Thus, it may change the state of the domain by enlarging the corresponding corpus of material and symbolic elements[3]. Following the domain extension, individuals may employ any combination of the old and the new symbols, techniques, tools and procedures to perform their creative activity. This amounts to a higher number of possible combinations of the elements of the domain (in mathematical terms, the power set of the

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[3] An interesting case to mention is computational creativity, whereby technology automatically generates a set of creative solutions (e.g. through generative design software). In this case, the technology can be regarded as an open-ended element capable of generating further elements in a given subdomain (e.g. design).

domain gets larger). Since those combinations act as a basis for the individual to generate novel and effective (i.e. creative) output, an increase in their number complements workers performing creative tasks.

We propose that the stronger the worker's domain-relevant skills, the larger the subdomain spanned by the worker, and thereby the higher the increase in the number of possible combinations triggered by the technology-driven domain extension. This is easily shown through combinatorics. Adding 3 elements to a starting set of 5 elements results in 224 additional possible combinations. If the starting set consists of 10 elements, the increase amounts to 7,168 combinations. With a starting set of 20 elements, the increase becomes 7,340,032. Although only a tiny fraction of the possible combinations may pave the way for novel and useful output, the exponential nature of the increase makes the size of the spanned subdomain an impactful complementarity channel. Still, it should be noted that the increase is only theoretical. The mere existence of a higher number of possible combinations of symbols, techniques, tools and procedures does not imply that a given worker will explore them. The ability and propensity of the worker to explore old and new combinations is determined conjointly by creativity-relevant processes and task motivation. The more individuals are creatively capable and motivated, the likelier they are to explore the (extended) space of combinations eagerly and fruitfully. This conceptual framing suggests that domain-relevant skills, creativity-relevant processes and task motivation are not only complementary among themselves (Amabile and Pratt, 2016), but also in relation to technological advancement.

Along the line of knowledge space literature (Doignon and Falmagne, 1985), basic set theory provides a more rigorous formalization for these insights. Given our definition of domain as a set, the power set of the domain represents the space of possible combinations of building blocks for creative outcomes. The power set of the subdomain spanned by the domain-relevant skills of a given individual represents the space of building blocks at the individual's disposal. The portion of the latter space actually explored by the individual is determined by his or her creativity-relevant processes and task motivation. Finally, domain-relevant skills, creativity-relevant processes and task motivation intervene conjointly in the process of exploiting the explored combinations of building blocks toward creative accomplishments. We propose that while the exploration of different combinations relies mainly on divergent thinking (Guilford, 1984), putting their constituents together in novel and effective ways relies on both divergent and convergent thinking (Cropley, 2006; Simonton, 2015). Convergent thinking grants clarity in the identification of the peculiarities of each element in the explored combination, while divergent thinking allows the individual to craft novel connections among them. Convergent thinking intervenes also in the act of selecting the most promising combinations among those explored, by estimating the novelty and effectiveness of the output they may lead to.

The complementarity mechanisms delineated above unfold with a technology extending a domain, an individual exploring and selecting among a (larger) set of combinations of symbolic and material elements and a field influencing the whole process. We suggest that the joining link between these constructs lies in a peculiar category of creativity-relevant processes: heuristics. We define heuristics as cognitive shortcuts, automatisms, practical strategies and simplified avenues to creative solutions. They have been shown to affect creative performance considerably, through their role in the execution of multiple processes underlying creative thought, such as problem construction, information encoding and category search (Mumford et al. 1991). In many instances, their impact is so significant they can also be used as a basis to evaluate creative performance (Vessey and Mumford, 2012), and even improve it through training (Scott et al., 2004). Grounded in past experience, heuristics constrain the exploration of the space of possible combinations of domain elements within preconceived tracks, due to their proved effectiveness. Despite their benefits to creative efforts, we propose that heuristics can become impediments to the full exploitation of a domain extension, for the very reason that they are rooted in consolidated bodies of knowledge and practice. When a domain evolves, old heuristics may cease to be adequate, and need to be replaced with new ones tailored to the new domain (Lenat, 1982). Still, individuals are likely to continue employing the outdated heuristics even in the presence of novel elements, by force of habit. Only after a prolonged exposure to the extended domain will they progressively develop heuristics for it. The use of outdated heuristics may make the individual blind to (a part of) the additional combinations granted by the technology-driven domain extension, dampening the complementarity mechanisms.

Although heuristics always require time for updating, we suggest that the field plays an important role in accelerating the process. Ex ante, the field may propose new frameworks, approaches and practical strategies related to the newly adopted technology. This may happen through top-down directives, business seminars and ad-hoc training sessions. While not automatically leading to heuristics optimized for the extended domain, these initiatives would constitute a first step toward the acknowledgment of change, weakening the persistence of old heuristics. Ex post, the field may stimulate heuristics renewal by recognizing and rewarding the presence of newly introduced symbolic and material elements in the individual recombinatory efforts. Rewards, in the form of implicit and explicit feedbacks, will dynamically incentivize employees to explore the extended space of possible combinations. This helps them to start the virtuous circle of heuristics development, consisting of search strategies optimized for the extended domain and new connections between old and new symbolic and material elements. Such creativity-relevant processes are essential not only in the exploration phase, but also in the exploitation of the selected combinations of elements toward creative accomplishments.

So far, we have implicitly abided by the restrictive notion of field as the ensemble of gatekeepers to the domain. Thus, we have referred mainly to the management of the organization. However, a looser definition of field as the entirety of the social context where employees operate may offer additional insights. From this perspective, interactions among employees at the same hierarchical level are equally impactful. Like technology (Geroski, 2000), new heuristics might undergo word-of-mouth patterns of diffusion within the organization, whereby the probability that new employees start using the new heuristics depends on the number of employees already using them. The analogy is far from perfect, as heuristics renewal is a gradual process rather than a dichotomous event, even at the individual level. Furthermore, heuristics diffusion is not only about transfer of information, but also about the active transmission of a practice, which may encounter well-known problems like lack of motivation, lack of absorptive and retentive capacity, and arduous relationships between transferors and recipients (Szulanski, 1996). Still, sharing the same heuristics engenders self-reinforcing dynamics. For instance, it progressively enhances coordination among employees and builds adaptive expectations, whereby employees become likelier to adopt the same heuristics even just because they expect others to do the same (Schreyögg and Sydow, 2011). Thus, we suggest that diffusion dynamics are an important part of the process whereby the field progressively recalibrates heuristics. Although diffusion is likely to be spontaneous, it may still be affected by factors like employee cohesiveness, team structure, network dynamics, organizational culture, and even by the nature of the domain-extending technology itself[4]. This provides managers with additional levers to accelerate the heuristic renewal process.

The following figure provides a graphical representation for the interactions described in this Section.

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4. An empirical illustration: AM in Luxottica

In this Section, we present an exemplification of our conceptual framework. Far from a rigorous case study, it should only be intended as a fitting instantiation of our theoretical contribution, aimed at illustrating how the conceptualized dynamics unfold in practice[5].

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[4] For example, technologies that facilitate distant communication and sharing of information (e.g. social networks) may lead to isolation and social alienation. If the domain-extending technology is of this kind, it may reflect negatively on the speed and effectiveness of the diffusion of heuristics. In principle, it could also reflect negatively on collaborative creativity. Although the team level of analysis falls outside the scope of this work, the trade-off between individual and team-level effects of different technologies on creativity may be an interesting topic for further studies.

[5] Despite the limited purpose and scope of our narrative, we still followed a rigorous methodology in gathering and analyzing data. Please refer to the Appendix for further details.

4.1. The AM technology

AM denotes the production technique of recreating a whole through layer-by-layer overlapping of material through a 3D printing machine, proceeding from a digital model[6].

On the digital side, 3D printers make use of CAD software, benefiting from innovations like solid modelling and point cloud. Likewise, they have benefitted from the introduction of 3D scanners, both for replication purposes and, more interestingly, for the possibility to engage in the creative editing of 3D-scanned objects. Instead, automation is a feature they share with computer numerical control machines. Once the model is ready, the integrated CAD software generates a set of instructions for the fabricator to reproduce the required object. In the case of CNC machines like lathes, the instructions prescribe reproduction by subtraction of material; conversely, with AM, reproduction is achieved through layer-by-layer addition. Structural features like the number of printing heads, the number of axes of motion and the type of motors contribute to determining printing speed and accuracy.

While subtractive manufacturing excels at large scale production by exploiting economies of scale and modularization, AM compresses the production pipeline into the two-step process of designing and printing, making it ideal for small-size batches. Economic benefits of AM have been researched extensively (Petrovic et al., 2011; Berman, 2012; D'aveni, 2013; Attaran, 2017). They range from rapid spare parts production to mass customization and supply chain compression. We consider two of such benefits to be particularly relevant to creative tasks: rapid prototyping and higher freedom in design. Final products typically require several iterations of prototypes, to test for structural and geometrical features. By their very nature, prototypes do not generate the economies of scale on which

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[6] The digital model of an object, developed through CAD software and/or 3D scanners, is transmitted to a 3D printing machine. Then the model is decomposed into 2D layers, which one or more printing heads reproduce and juxtapose. Materialization of layers stems from the binding of liquid, powder or solid inputs. Depending on the input, different fabrication processes exist: examples are vat photopolymerization, powder bed fusion and directed energy deposition. Heterogeneity in fabrication processes enables the optimal treatment of materials of a different nature, ensuring wide applicability.

traditional manufacturing thrives. Additive manufacturing of prototypes is much faster, resulting in reduced time-to-market. The resulting increase in speed and efficiency incentivizes experimentation, and thereby creativity. Secondly, AM enables the reproduction of complex product shapes and geometries that would be difficult or impossible to reproduce with other methods. This brings both functional benefits, as in the case of honeycomb structures in the aerospace industry (Misra, Grady and Carter, 2015), and aesthetic benefits, which are especially relevant for design-oriented industries like fashion and jewelry (Yap and Yeong, 2014).

In manufacturing industries where aesthetics matter, design is a crucial value creating activity. In this context, designers use their visualization, imagination and drawing skills (individual) to create aesthetically appealing output, with a well-defined set of tools (domain) and following precise ideation heuristics, conforming to market-driven and sociocultural criteria (field). By releasing design constraints, AM triggers a domain extension. New geometrical configurations represent additional elements in the focal domain. When creatively combined, they lead to the emergence of jewels and accessories with shapes that used to be unthinkable. The range of creative opportunities gets even larger by linking the new domain elements with extant ones, namely by integrating additive and subtractive techniques.

Regarding the interaction between AM and creative tasks, design heuristics are a crucial determinant of performance. The role of heuristics in facilitating the exploration of the space of possible designs is indeed well-acknowledged (Yilmaz et al., 2011; Daly et al., 2012). Design heuristics vary in their degree of specificity, ranging from circumscribed spatial manipulations to the embedment of cultural elements in the design of objects (Yilmaz and Seifert, 2011). The shift from traditional manufacturing to AM is particularly interesting in this sense, as it generates a clash between the class of heuristics that favor simplicity versus those that favor complexity. In the case of traditional manufacturing, optimized for modularization, “simple is better” is a very powerful heuristic, which contrasts with the “complexity for free” motto of AM. However, while AM and traditional manufacturing substitute for each other in many instances, they may actually be complements in creative tasks. Thus, employees should develop design heuristics connecting the symbolic and material elements of traditional manufacturing with those of AM. In order to exploit AM fully, designers might need to frame modularity as an additional tool rather than a constraint, and develop heuristics for the integration of AM-enabled complexity and traditional product modules. In this endeavor, they may also leverage complementary technologies like generative design software, for their capability of spawning unconceivable shapes automatically, thereby bridging the gap between known and uncharted territory.

Not only is AM a good example because of the introduction of heuristics contrasting with the status quo, but also due to the coexistence of the classic efficiency-based complementarity channel (Autor et al., 2003) and the new domain-based channels that we propose. Such channels coexist indeed in the very relationship between AM and the creative task of design. On the one hand, AM-enabled rapid prototyping incentivizes experimentation and creativity by reallocating time and energy thanks to process-based efficiency gains and improvements in the quality of inputs to the creative task. On the other hand, AM complements workers performing the creative task of design by providing them with new domain elements to combine toward creative accomplishments, in interaction with their domain-relevant skills, creativity-relevant processes and task motivation. This duality makes AM particularly well-suited to illustrate the distinctiveness of the dynamics that we have conceptualized.

4.2. 3D-printing eyeglasses in Luxottica

Luxottica is a global leader in the high-end eyewear sector, with 9 billion euros sales, 82000 employees worldwide and a distribution network spanning 150 countries (annual report 2018). Brand image maintenance and international competition maximize Luxottica’s incentives to adopt the latest technological solutions to keep its premier position in the market. Additionally, Luxottica has a specific drive for innovation. Innovative thinking is well-rooted in the company’s heritage, with its R&D team pioneering many breakthroughs in frames and sun lenses through intensive experimentation, leading to more than 950 utility, design and technology patents worldwide (annual report 2018). The company is committed to the digital transformation, heavily investing in advanced technologies like AM[7], robotics and big data analytics. Furthermore, Luxottica strives for excellence in the human resource department, emphasizing the value of craftmanship and creativity. Luxottica regards both the technological and the human side as key factors of competitive advantage, and employs them conjointly for creative accomplishment. These factors altogether make it the ideal context to observe the interaction between AM and workers performing creative tasks.

Luxottica has employed AM for plastics since 1998. Since 2015, thanks to a partnership with the Swedish company Digital Metal, it has been using it also for metal. As stated in the official article emblematically titled "3D printing at Luxottica: total freedom of form", AM has brought two main advantages: an acceleration of the production process, and increased freedom in both the creation and the production process of eyeglasses. As confirmed in the interviews, these advantages are reflected in the use of AM for rapid prototyping/tooling and final product manufacturing (*"here we see 3D printing as having two great souls: one soul concerning the 3D printing of the plastic part and the other soul relating to the 3D printing of the metal part. We identify the focus of 3D printing in three large areas: 1) prototyping: ease of product development; 2) service for factories (therefore, the possible use for tooling both for the factory and for its maintenance); 3) the possible use of the technology in the context of actual production to insert it into a model that will then be sold").* While AM is useful in the design process of most eyeglasses for prototyping, tooling and refinement, 3D printed final products are typically destined to boutiques in limited editions.

Rapid prototyping is highly beneficial in the design phase, where it accelerates the verification of shapes, geometries and functional requirements. To this end, the benefits of 3D printed tools have also been stressed. The possibility to rapidly print both prototypes and tools as the need arises facilitates design iterations, encouraging experimentation and creativity ("*with standard technologies*

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[7] Please note that AM is informally referred to as 3D printing in the interviews.

it is really necessary to think a lot about how to do some things which probably require 3-4 iterations of molding, 3-4 iterations of forming, 3-4 iterations of tooling and more. With 3D printing, on the other hand, once you understand what you want to achieve, the result is immediate”). This confirms that AM may complement workers performing creative tasks by improving the quality of inputs and the overall efficiency of the process.

However, AM also extends the set of domain elements at designers’ disposal. In particular, it allows designers to play with internal cavities, undercuts and nested transparencies, leading to richness and complexity in design (“*with 3D printing, you can make all those geometries that have undercuts, hollow parts, where you can see transparent parts one behind the other, then games of internal constructions that are seen transparently even on external constructions*”). In this respect, it is worth stressing that traditional manufacturing has been mentioned as a complement to AM (“*to reach the market, 3D printing needs traditional manufacturing technologies, for example surface refinements and coloring; therefore a key factor for 3D printing is how to adapt existing processes to the use of 3D printing*”). This remarks that AM triggers a domain extension, and not a domain substitution, requiring extant domain-relevant skills alongside creativity-relevant processes that favor the integration of established symbolic and material elements with new ones. In the context of AM, this amounts to creatively integrating the strengths of additive and subtractive techniques, together with complementary technologies like 3D scanning (“*3D scanning, namely the ability to digitally render physical objects, is certainly an enabler for the use of 3D printing technologies*”).

Luxottica as an organization (i.e. the field) seems to be aware of the heuristics renewal challenge during the transition to a new, extended domain. Even though heuristics have never been mentioned explicitly, a mentality adaptation issue has emerged. Designers are not always conscious of the full potential of AM. This prevents them from exploring and exploiting the additional combinations of elements enabled by the new technology (“*perhaps a difficulty is letting people enter into the logic of being able to do whatever they want to do, because sometimes they have limitations, because maybe* *they have a mentality connected to, let's say, standard production systems"*). However, rather than sourcing specialized designers from the outside, Luxottica strives to nurture the extant workforce internally, helping employees in the transition toward new heuristics through intra-organizational knowledge diffusion mechanism ("*as far as we are concerned, we do not seek particular external expertise...but what we do here inside is to carry out a process of knowledge and education regarding the constraints that could be removed with this technology. We made a mental effort ourselves in the first place, and then tried to communicate the fact that some constraints could be struck down"*).

Although the potential of AM in the eyewear business is still far from enabling large-scale manufacturing of final products, this case clearly illustrates that AM complements designers not only through standard efficiency gains, but also through a domain extension. AM does not only accelerate the production process and improve the quality of inputs to the design creative task, but it also enables the inclusion of twists, cavities, transparencies and novel geometries in the design of products. Due to the required integration with traditional manufacturing, full exploitation of these new elements requires a workforce that is skillful in the domain besides creative and motivated ("*for excellent products you need excellent people. This is a perfect correlation and there is no automation or technology that can reverse it. After all, to date, creativity is still exclusively a human factor and the quality of creativity is strictly linked to the quality of people, to how expert and open-minded they are"*). The case of Luxottica also illustrates that the full exploitation of the domain extension is not immediate. Instead, it requires time and adaptation, and the organization has an important role in accelerating the process. It is worth stressing that the market for eyeglasses produced with AM is still rather small, and limited to boutique collections and small-scale special editions. Yet, the company devotes significant effort to optimizing the creativity-relevant processes of the employees working on them. This makes the case even more interesting, as we can only assume these dynamics to get stronger as the scale of operations increases, making the corresponding creative task more impactful financially and strategically.

5. Discussion and conclusion

The present work contributes to two areas: the labor-oriented stream dealing with the relationship between employees and non-routine tasks (Autor et al., 2003; Levy and Murnane, 2013), and the creativity-oriented stream focused on employees as generators of ideas and innovations (Shneiderman, 2002, 2007; Dewett, 2003; Lubart, 2005). To the best of our knowledge, the former has never gone beyond classic efficiency-based complementarity channels between technology and workers performing non-routine cognitive tasks, based on the reallocation of time and effort and improvements in input and process quality. Focusing on creative tasks, the creativity-oriented stream provides valuable insights on technology as a creativity support tool, bolstering search, storage, visualization, computation, communication and many other functions allowing workers to gather, share and manipulate knowledge more easily, turning it into novel and effective output. This perspective keeps the focus on creative individuals, who use technology as a facilitator of the creative process. Overall, creativity support tools can be framed as an expression of the aforementioned efficiency-based complementarity channels in the area of creative tasks. Indeed they either improve the efficiency of a process (e.g. search, computation, dissemination) or the quality and/or quantity of some inputs (e.g. visual or auditory stimuli).

We have proposed an additional way whereby technology may complement workers performing creative tasks. Our perspective shifts the focus from the individual to the interaction between the individual, the domain and the field (Csikszentmihalyi, 1996) and considers the potential of technology to extend the domain. Since the creative output stems from the (field-mediated) interaction between the domain and the individual, the possibility of a technology-driven domain extension engenders dynamics of complementarity between the extension itself and the determinants of individual creativity, namely domain-relevant skills, creativity-relevant processes and task motivation (Amabile, 1983, 1988; Amabile and Pratt, 2016).

We suggest that domain-relevant skills determine the size of the subdomain available to the creative individual, while creativity-relevant processes and task motivation determine, respectively, the ability and propensity of the individual to scan the extended domain for novel combinations of symbolic and material elements. All these factors enhance each other. While the complementarity of the three determinants of individual creativity is not new, the idea that each of them complements the technology-driven domain extension is something to become aware of. The stronger the domain-relevant skills, creativity-relevant processes and task motivation of the individual, the more beneficial the technology-driven domain extension. While stronger domain-relevant skills determine a larger pool of potential combinations of old and new elements, stronger creativity-relevant processes and task motivation determine the subset of those combinations that is actually explored and exploited toward creative accomplishments.

Our framework also recognizes the special role of heuristics as a dynamic joining link between the field, the domain and the individual. Constituting useful cognitive shortcuts and practical strategies optimized for a given domain, heuristics are essential in most creative endeavors (Mumford et al. 1991; Scott et al., 2004; Vessey and Mumford, 2012). For example, in design tasks, they facilitate the exploration of the space of possible shapes (Yilmaz et al., 2011; Yilmaz and Seifert, 2011; Daly et al., 2012). However, being persistent and rooted in the old domain (Lenat, 1982), extant heuristics may dampen the creativity-enhancing potential of new technologies at first, which require new heuristics. While the transition to new heuristics is likely to be spontaneous, the mobilization of managerial and organizational levers, both ex ante (e.g. training sessions, internal seminars, goals, formal and informal incentives) and ex post (e.g. feedbacks, rewards and penalties) may facilitate and accelerate the process. We propose that the presence of heuristics tailored to the new extended domain is a crucial determinant of the technology-driven improvement in creative performance. Thus, the awareness and proactivity of the field are important supporting factors, especially in the short term.

From a theoretical viewpoint, our perspective also sheds new light on the sociocultural view of materiality (Glăveanu, 2020), which underlines the complex interaction between individuals and objects in the generation of creative solutions. Technologies are a peculiar category of objects characterized by higher complexity, usefulness and manipulative power on reality. Furthermore, they undergo incessant upgrading, which may be incremental or radical. Our analysis reveals that when objects have such characteristics, their interaction with individuals should be framed dynamically, focusing on the context-dependent evolution of their approach to the object. It is also worth noting that our perspective does not invalidate or weaken the idea that technology may support creativity through input or process mechanisms. On the contrary, the two perspectives are complementary. In the face of a domain extension, creativity support tools may be even more useful than usual, as they offer additional ways to gain expertise and explore the space of possible combinations. Thus, creativity support tools may be framed as enhancers of domain-relevant skills and creativity-relevant processes, which contribute alongside task motivation to reaping the full benefits of a domain extension.

From a managerial viewpoint, the present work has three main implications. First, it shows that technological advancement and workers performing creative task are complementary in complex, dynamic ways. This is something managers should keep in mind, both when considering technology adoption and when hiring, organizing and training human resources. Domain-relevant skills, creativity-relevant processes and task motivation should all be taken into account in conjunction with technology adoption. Since the lack of even one factor may potentially nullify the creative benefits of a domain extension, it becomes essential to consider them conjointly and envisage avenues for improvement aimed at preventing bottlenecks. Second, the present work underlines the role of the creative leaders in unleashing the creative potential of employees (Mainemelis et al., 2015), especially in conjunction with new technologies. This is because new technologies trigger domain extensions, which require new heuristics. Creative leaders have a pivotal role in accelerating the transition to new heuristics, by providing adequate goals, feedbacks and directives. Third, managers should not only encourage the transition to new heuristics directly, but also pave the way for it indirectly. As heuristics are likely to undergo spontaneous dynamics of diffusion among employees (Geroski, 2000), especially through imitation, coordination and adaptive expectation effects (Schreyögg and Sydow, 2001), managers should optimize diffusion by increasing the absorptive and retentive capacity of employees and preventing obstacles like arduous relationships between sources and recipients (Szulanski, 1996). If data allow for it, managers may even use their knowledge about the structure of the social network within the firm to devise an optimal diffusion plan, for example by instructing and training the most influential people first. This may contribute to a faster and smoother transition to the new corpus of heuristics.

Finally, we contribute to the debate on the relationship between skills and technology in the digital era by offering an alternative view. While technologies comprising the Fourth Industrial Revolution are likely to substitute for some worker categories, those technologies themselves also contribute to complementing workers in novel ways. Although we explored only the AM case, we believe that our notion of domain extension may be applicable to other advanced technologies (e.g. AI, which instead is mostly studied for its substitutive effect on labor).

The present work shows that domain-driven complementarity between technology and workers performing creative tasks is theoretically solid. It also elucidates its dynamics in the case of AM and Luxottica. From an empirical viewpoint, comparing the AM case with other technologies and, more generally, other domain-extending events may offer additional insights. This way, our framework may potentially be adapted to non-routine cognitive tasks other than creative tasks, and domain extensions driven by factors other than technology. In order to deepen the aspects related to heuristics development and managerial support, it would also be interesting to analyze the same domain-extending event in different organizational contexts. Another valuable research endeavor would be an investigation of the role of convergent and divergent thinking in the face of a domain extension.

While we advanced some basic propositions in this direction, more focused inquiries grounded in applied psychology would certainly be beneficial. Lastly, while we conducted our analysis mainly at the individual level, our domain-centered perspective may offer valuable insights also for collaborative creativity and team-level inquiries. Given the increasing importance of creativity and the speed at which domains grow and blend with each other, these are all promising research paths.

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Appendix

Our illustration follows a nested exemplification logic. AM represents a relevant domain-extending technology, while Luxottica constitutes the ideal organizational context to observe AM-driven interactions between the field, the domain and the individual.

Despite not aiming for a case study, we still adhered to a rigorous protocol of data gathering and analysis, to ensure reliability of the information underlying our narrative. After identifying AM as a relevant technology, we gathered technical contributions on it, drawing from journal articles, grey literature and well-established specialized sources (Wohlers Report, 2019). This preliminary step served the purpose of identifying the way in which AM could extend the domain of creative tasks. Subsequently, we identified Luxottica as a relevant company and searched for official documents on the topic. We downloaded annual financial reports and reviews from 2003 to 2018 (all available years), and searched for press releases, official articles and public interviews on Luxottica's approach to AM. We stored official documents in a dedicated database, screened them for relevant content and triangulated them as an initial check for internal consistency, with no anomaly revealed.

After depicting an overview of the company and its approach to AM, we investigated the interactions between the field, the domain and the individual by interviewing the global R&D director and the frames R&D manager of the company[8]. The rationale for interviewing these roles lies in our willingness to obtain a twofold viewpoint on the focal dynamics. While both roles offer a broad, informed perspective on the interaction between AM and creative tasks in the company, the global R&D director brings more managerially-oriented insights, whereas the frames R&D manager deepens the technical side. Building on our key constructs, we adopted a semi-structured interviewing scheme, in order to maintain thematic relevance while allowing interviewees to stress the most important points autonomously. Whenever possible, the information was triangulated with the aforementioned secondary sources, to ensure reliability (Yin, 2009). Interviews were transcribed verbatim, coded and categorized according to well-established practices in qualitative research, such as in-vivo, process and causation coding (Saldaña, 2015). Other highly specific material (e.g. official articles on AM) was also coded entirely. Instead, official reports and reviews were preliminarily screened to identify the most relevant Sections to code (e.g. design, R&D and innovation). The following table summarizes the research protocol and the coding strategy.

INSERT TABLE I ABOUT HERE

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[8] While obtaining interview data directly from designers would have been preferable, it is worth noting that the frames R&D manager constantly interacted with them. Thus, he was in a privileged position to report their behavior in relation to the focal topics. Hence, given the merely illustrative purpose of the case study, we regard this limitation as acceptable.

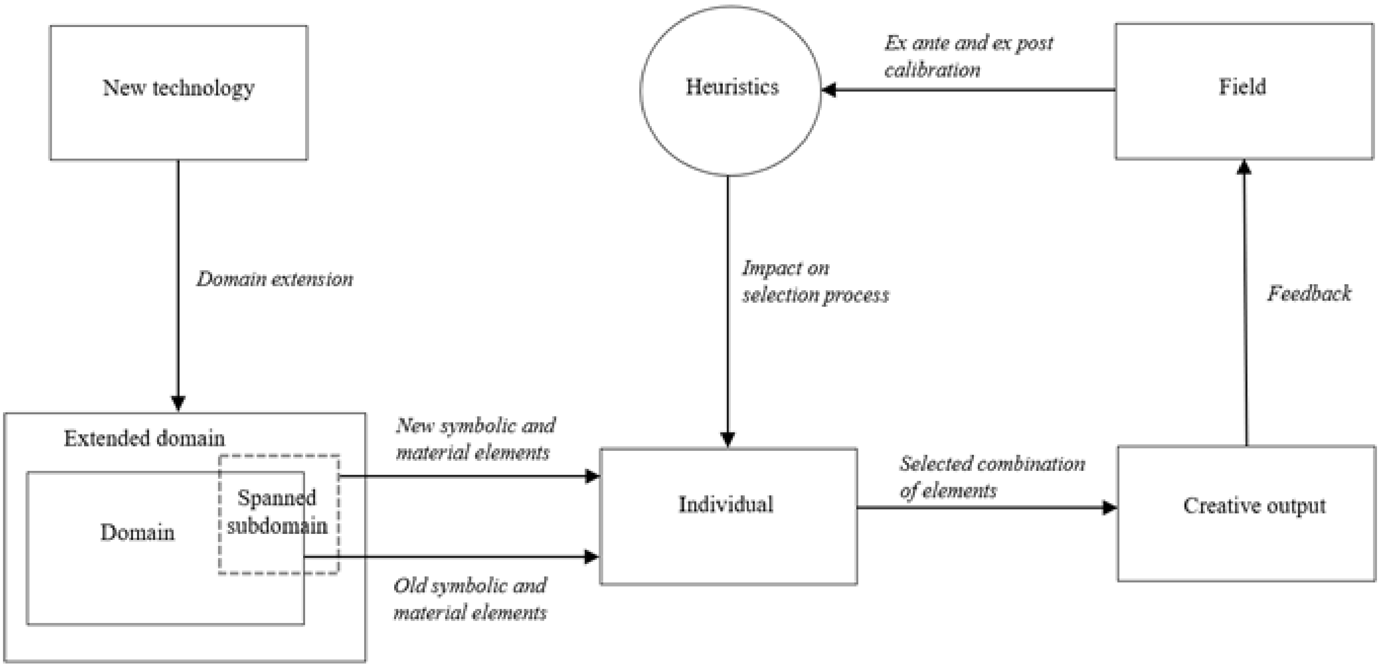

Figure 1. A graphical representation of our conceptual framework of domain-driven complementarity between technology and workers performing creative tasks

Data Source	Purpose	Type of analysis
Technical literature on AM, specialized sources (e.g. Wohlers Report 2019).	Defining the peculiarities of the focal technology in relation to creativity.	Explorative analysis of the Wohlers Report followed by a selective literature review on focal aspects and characteristics of the technology.
Official Luxottica annual reports and reviews from 2003 to 2018 (all available years); press releases and articles on AM.	Defining the firm context and ensuring the reliability of primary data through triangulation.	Preliminary screening followed by selective coding (only relevant sections were coded).
Interviews with the global R&D director and the frames R&D manager of the company.	Getting an overview of the AM-driven interactions between the individual, the domain and the field from both a technical and a managerial viewpoint.	Mix of in-vivo, process, descriptive and causation coding followed by categorization and association to key constructs (i.e. individual, domain, field, domain-relevant skills, creativity-relevant processes, task motivation, heuristics).

Table I. A summary of the protocol for data gathering and analysis.