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Market value of R&D, patents, and CEO characteristics

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Abstract

The contribution of knowledge capital to firm value has increased significantly, from 25% in the 1970s to 45% in the 2010s (Belo et al. in Decomposing firm value J Financ Econ 143:619–639, 2022). However, what influences firms' ability to maximize the effect of knowledge capital on firm value? Drawing on insights from upper echelons, agency, and behavioral agency theories, we show that CEO characteristics are crucial in enabling firms to take advantage of knowledge stock. We empirically demonstrate that short-term CEO compensation structures are detrimental to a firm's ability to take advantage of its knowledge stock. We further show that CEO power enhances knowledge stock and R&D intensity. Our study provides direct empirical evidence of the importance of CEO compensation structure and corporate governance in understanding firm value in a knowledge economy.

Keywords: Innovation, Patent, Market value, CEO power, CEO compensation

JEL Classification: G10, O31, O32

Introduction

Assessing return on innovation investment is important for existing and new shareholders and, to date, there is extensive literature on the impact of knowledge characteristics on firm market value (Arora et al. 2021a; Hall et al. 2007, 2005). However, given the important role that chief executive officers (CEOs) play in firm performance (Custódio and Metzger 2014; Benmelech and Frydman 2015; Mukherjee and Sen 2022), it is surprising that the literature remains silent on the effects of CEO characteristics on return on investment in innovation. This study aims to fill this gap in the literature.

Investing in research and development (R&D) is a complex process with a relatively unknown and stochastic outcome (Kline and Rosenber 2010). Theoretically, R&D is an investment activity that produces an intangible output known as "knowledge stock" (Hall et al. 2005). Furthermore, the value of knowledge stock that contributes positively to a firm's future cash flow should be reflected in its market value. Previous studies have empirically used innovation output measures such as the number of patents and citations to measure the amount of knowledge stock created by R&D investments (Blundell et al. 1999; Hall et al. 2007).

Some R&D investments create valuable knowledge stock for firms; otherwise, firms have no incentive to invest in R&D. However, Mansfield et al. (1977) identify three different stages of innovation that determine the probability of R&D investment success. First, the creation of significant knowledge stock depends on the probability that technical goals will be met. Technical success is achieved when a product that has undergone the development and testing phases is finally launched (Dean et al. 2022). Second, knowledge creation depends on financial success. Financial success is achieved when the cumulative costs of innovation activities are covered (hitting the break-even point), and the firm obtains a net positive difference between overall revenues and total costs (Teece 1986). Third, knowledge creation depends on commercialization success. Commercialization success is achieved when the product attracts an expanding customer base and when its current revenues surpass its current costs (Hudson and Khazragui 2013). Firms need to invest significant time and resources in transforming their growth in valuable knowledge, such as patents, into actual economic success. They must overcome the uncertainty at each stage, and failure at any point implies that a firm will bear the costs without realizing the anticipated benefits (Coad and Rao 2008). In this case, it is important to understand how a company can achieve higher market value for patents in such an uncertain process.

The literature explores knowledge capitalization from two perspectives. The first examines how a firm's innovative activities increase its market value (Griliches 1981; Cockburn and Griliches 1987; Blundell et al. 1999; Hall et al. 2005, 2007; Arora et al. 2021a). The second stream concerns the technology spillover of R&D investments (Jaffe 1986; Bloom et al. 2013; Arora et al. 2021b). In light of these perspectives, we argue that previous literature on knowledge capitalization has predominantly focused on knowledge characteristics, neglecting internal management aspects within companies.

However, given the unpredictable nature of the innovation process, identical levels of R&D investment can lead to the formation of diverse knowledge assets (Hall et al. 2005). Drawing on insights from upper echelons, agency, and behavioral agency theories, we conjecture that CEO characteristics play a crucial role in the process of converting R&D investments into valuable knowledge stock for the firm.[1] CEOs hold the highest position in a firm's management team (Barnard 1968; Djebali and Zaghdoudi 2020) and bear the responsibility for managing and supervising corporate affairs (Hambrick and Mason 1982). Although strategic decision making involves the participation of other top management team members and the board of directors, CEOs are generally anticipated to play an assertive and proactive role in shaping strategic formulation (Sariol and Abebe 2017). They can define the institutional mission and goals (Bhaskar et al. 2023), steer firms in actively pursuing opportunities (Barnard 1968), and govern their structures and strategies (Woodward 1965; Lawrence and Lorsch 1967).[2] In this context, differences in CEO characteristics can cause firms

[1] Previous literature clearly demonstrates a significant relationship between CEO characteristics and firm performance (e.g., Bamber et al. 2010; Barker and Mueller 2002; Farag and Mallin 2018).

[2] There is extensive empirical literature investigating the impact of CEO characteristics on firms' actions and outcomes in corporate financing decisions and financial policies (Bamber et al. 2010; Jiang et al. 2010; Demerjian et al. 2013), innovation strategy (Daellenbach et al. 1999; Barker and Mueller 2002; Lin et al. 2011; Durendez et al. 2023), time to initial public offering (Hambrick and Mason 1984; Yang et al. 2011), corporate social responsibility decisions (Campbell 2007; Di Giuli and Kostovetsky 2014; Muttakin et al. 2018) and risk-taking activities (Coles et al. 2006; Farag and Mallin 2018).

to display varied approaches to productization, marketization, and revenue generation processes, culminating in unique results.

We report several findings from this study. First, we demonstrate that CEO age plays an important role in converting knowledge stock into market value. Younger CEOs tend to generate higher innovation investment returns. This finding is in line with the previous literature that younger CEOs are more willing to undertake new and riskier projects (Li et al. 2017). Second, we find that more powerful CEOs tend to generate higher return on innovation investment. We posit that this result relates to the desire of powerful CEOs to lead enlarged, intricate, and diversified firms (Baker et al. 2012). This finding also relates to the fact that powerful CEOs are more likely to view the capitalization process of knowledge stocks as "loss aversion" strategic decisions, therefore leading them to take riskier strategic decisions. Third, when CEO compensation is closely tied to the firm's long-term profitability, the firm's knowledge stock tends to generate a larger market value. This is in line with previous findings that long-term financial rewards incentivize CEOs to act in the organization's best interests and make decisions that enhance firm performance (Bhaskar et al. 2023).

The contribution of this study is twofold. First, several studies investigate the return on innovation investment (see Blundell et al. 1999; Hall et al. 2007). This is because R&D expenditure is expensive and has a long-term and uncertain payoff. Therefore, it is crucial to identify whether investments in innovation increase firm value. Relatedly, there is extensive literature on the impact of knowledge characteristics on a firm's market value (e.g., Arora et al. 2021a; Hall et al. 2007, 2005). The overarching finding of this literature is that firms' ability to capitalize on their knowledge stock varies extensively according to firm and knowledge characteristics. This study contributes to the existing literature by demonstrating the role of CEO characteristics. This is important because understanding the role of CEO characteristics in knowledge capitalization allows firms to increase their return on innovation.

Second, several studies have examined the impact of CEO characteristics on firm performance (Benmelech and Frydman 2015; Custódio and Metzger 2014; Mukherjee and Sen 2022). These studies concur that the CEO plays the most decisive role in a company's success or failure. One of the decisions the CEO must make is whether to invest in innovation; however, to date, no studies have been conducted on the impact of CEO characteristics on the ability of the firm to increase return on innovation. This study contributes to the literature by demonstrating that one of the paths via which CEO characteristics affect firm performance through knowledge capitalization. This is important because it answers the long-standing puzzle of how identical levels of R&D investment lead to different firm values.

The remainder of this paper is organized as follows. Section "Literature review and development of hypotheses" reviews the relevant literature and develops several hypotheses. Section "Data and methods" describes the sample and variables. Section "Analysis" presents the analysis. Section "Robustness test" presents the robustness tests. In Section "Effect of CEO compensation", we test the effects of CEO compensation, and Section "Conclusion and Implications" concludes the paper and discusses the study's implications.

Literature review and development of hypotheses

Literature review

Theoretically, investments in innovation may contribute to firm value for several reasons, which are mainly based on resource-based perspectives (Nason and Wiklund 2018). When a firm invests in innovation-specific assets, it contributes to its unique resource bundle. Resource-based theory suggests that a firm is a pool of tangible (e.g., plant and equipment, inventory) and intangible (e.g., knowledge assets) resources that create unique capabilities over competitors and, in turn, provide new economic value to the firm (Mishra 2017; Nason and Wiklund 2018). Although the firm could maintain its competitive advantage when these capabilities and resources are valuable, their valuations are driven by the extent to which "*it exploits opportunities and/or neutralizes threats in a firm's environment*" (Barney 1991, p. 105). Markman et al. (2004) suggest that innovation creates intangible knowledge assets that are inimitable and non-substitutable. Under these circumstances, we capture the economic value of a firm's knowledge stock based on its stock market reaction to patents. A patent grants its owner the authority to prevent others from producing, utilizing, or commercializing an invention for a specified duration. This ability is highly efficacious in limiting competition, thereby generating significant private profits (Kogan et al. 2017).

However, the superior values that arise from a firm's assets and capabilities are intricately intertwined and challenging to individually appraise in the market (Hall et al. 2007). Griliches (1981) shows that a firm's market value reflects the present value of the forthcoming cash flow of its assets and capabilities. This approach has been applied in numerous studies to ascertain the marginal shadow value of knowledge assets within various companies (Griliches 1981; Hall 1993; Hall et al. 2005; Bloom et al. 2013; Arora et al. 2021a). The model is expressed as follows:

$$Value_{i,t} = q_t \left(Assets_{i,t} + \gamma \ Knowledge_{i,t} \right)^{\sigma} \quad (1)$$

where $Value_{i,t}$ is firm i's market value in year t, $Assets_{i,t}$ is the stock of tangible assets, and $Knowledge_{i,t}$ is the stock of knowledge assets. The parameter σ enables nonconstant scale effects in the value function. All variables are nominal.

The market value equation has been investigated from two perspectives. First, previous studies have investigated how firm innovation affects its market value (Griliches 1981; Cockburn and Griliches 1987; Blundell et al. 1999; Hall et al. 2005, 2007; Arora et al. 2021a). For example, Griliches (1981) demonstrates that "intangible" capital, represented by R&D investments and patent counts, translates into market value for large United States (US) firms. Blundell et al. (1999) find that the impact of innovation on market value is more pronounced in firms with a greater market share. Nesta and Saviotti (2006) show that the integration of biotechnological knowledge has a positive impact on stock market value during the 1990s. Hall et al. (2007) compare the market value of patents granted by the US Patent and Trademark Office (USPTO) and by the European Patent Office (EPO). Their findings indicate a positive and statistically significant correlation between Tobin's Q and R&D as well as patent stocks; however, this association is observed only when patents are granted either by both patent offices or exclusively by the USPTO.

Several studies are concerned with the spillover effects of R&D expenditure (Jaffe 1986; Bloom et al. 2013; Arora et al. 2021b). For instance, Jaffe (1986) finds that external firms' R&D activities have a positive (negative) impact on the market value of firms with high (low) R&D investments. Bloom et al. (2013) demonstrate that firms achieve higher market value through technological spillovers from their rivals. Additionally, Arora et al. (2021b) find that firms can enhance their market value by maximizing the utilization of their internal knowledge while minimizing their reliance on knowledge from closely situated product market rivals.

To the best of our knowledge, the literature on knowledge capitalization has primarily focused on knowledge characteristics, rather than internal management aspects within companies.[3]

Nevertheless, various phases of innovation dictate the likelihood of R&D investment success, including technical, financial, and commercial success (Mansfield et al. 1977). Each phase entails uncertainties, and failure at any juncture results in a firm incurring costs without reaping the expected benefits (Coad and Rao 2008). Since CEOs bear the main responsibility of managing and supervising corporate affairs (Hambrick and Mason 1982), their characteristics lead to distortions in investment decisions, thereby influencing firm performance (Belenzon et al. 2019). In particular, upper echelons theory (Hambrick and Mason 1984) posits that strategic decisions contain highly complex and often ambiguous information; therefore, making perfectly rational decisions is not always feasible. Instead, while executives strive to be rational, they are also influenced by their experiences, behavioral factor values, and demographic characteristics. These characteristics are instrumental in predicting firm outcomes. Overall, this theory posits that variations in CEO demographic characteristics lead to differences in their cognitive orientations and values (Rajagopalan and Datta 1996).

According to agency theory, CEOs do not always make rational decisions or maximize shareholder wealth. They may prioritize personal gains over shareholder interests, leading to an escalation in agency costs. Therefore, firms link CEO compensation to stock performance to mitigate agency costs and maximize shareholder wealth (Ryan and Wiggins 2001). Although several studies argue that CEO pay-for-firm-performance contributes to firm accounting and innovative performance (Morck et al. 1988; Mazouz and Zhao 2019), empirical results from other studies are inconclusive (Balkin et al. 2000; Chang et al. 2010). The mixed results can be explained by the behavior of CEOs. Managerial power theory suggests that board structural arrangements are crucial for aligning CEO pay with firm performance. CEOs who serve as board chairpersons (CEO duality) have more controlling power and thereby influence the compensation structure and investment decisions (Core et al. 1999; Amzaleg et al. 2014).

Since agents' actions are bounded by loss aversion, as suggested by behavioral agency theory, powerful CEOs may be more likely to pursue a firm's knowledge stock capitalization given their preference for loss aversion in decision-making. Loss aversion is a predilection for riskier strategies to completely evade a foreseen loss, rather than opting for less risky alternatives that only mitigate the loss (Wiseman and Gomez-Mejia 1998).

[3] Previous literature clearly demonstrates a significant relationship between CEO characteristics and firm performance (e.g., Bamber et al. 2010; Barker and Mueller 2002; Farag and Mallin 2018).

Therefore, for a firm, successful innovation (i.e., successfully transforming knowledge assets into commercial products that can yield satisfactory returns) is associated with both high risk and high reward (Coad and Rao 2008; Mansfield et al. 1977). While it introduces novelty to a firm's product range and bolsters its market presence by broadening the scope of product offerings and the inclusion of new target markets, it also causes significant uncertainty regarding the likelihood of success (Coad and Rao 2008). In this context, powerful CEOs are more likely to view the capitalization process of knowledge stocks as "loss aversion" strategic decisions, aiming to minimize the loss of their wealth even though these activities inherently come with substantial uncertainty and risk (Sariol and Abebe 2017).

Development of hypotheses

Innovation and firm performance

The literature provides substantial support for the direct connection between innovation and firm value (e.g., Chambers et al. 2002; Eberhart et al. 2004; Ho et al. 2005). Although their findings lead to the opposing conclusion that firm innovation promotes or inhibits firm value, most results confirm the positive impact of R&D and patent stocks on firm value. For example, Hall et al. (2005) show that a firm's intangible stock of knowledge is the driver of stock market valuation and highlight that more value is generated by self-citations. Gu (2005) confirms the value-enhancing effect of citations that contain useful information about a firm's innovation capabilities. Simeth and Cincera (2016) find a positive relationship between innovation and firm value. By investigating the voluntary disclosure of innovation outcomes in peer-reviewed scientific journals, they further show that the financial market reacts immediately to the creation of scientific outcomes.

By contrast, Ho et al. (2005) find an insignificant impact of intensive investment in R&D on the one-year stock market performance of non-manufacturing firms. However, Chambers et al. (2002) argue that this issue may be driven by the time lag between knowledge creation and the realization of financial returns. Particularly, investors may be unable to recognize the accounting treatment of R&D expenditure on earnings, thereby mispricing R&D-intensive firms. Therefore, we propose the following hypothesis:

Hypothesis 1 Other things equal, return on innovation investment will be higher for firms that contain more knowledge stock.

The moderating effect of CEO age

It is commonly argued that CEO characteristics play a crucial role in firm investment decisions. In particular, there are trade-offs between the managerial approach and investment decisions of younger and older CEOs (Belenzon et al. 2019). Younger CEOs tend to be more willing to act within the company. For example, Li et al. (2017) find that younger CEOs are more inclined to embark on new projects as indicators of their competence in the executive labor market. In contrast, older CEOs might prioritize their future financial stability and be sensitive to the risk of diminishing personal wealth (Belenzon et al. 2019). Bertrand and Mullainathan (2003) argue that CEOs tend to prefer less stressful work environments. These preferences are likely to become more pronounced with age. Additionally, age is often associated with office tenure, which contributes to psychological changes. Agency issues are more salient in the later stages of CEO tenure because they pursue stability and experience low interest in innovation strategies (Barker and Mueller 2002; Zona 2016). Therefore, we propose the following hypothesis:

Hypothesis 2 Other things equal, return on innovation investment will be higher for firms managed by younger CEOs.

The moderating effect of CEO compensation

CEO compensation has been widely investigated as an important motivation for CEOs to improve firm performance. Several studies report a significant positive relationship between executive compensation and risky strategic decisions. Sanders (2001) shows that when CEOs are compensated with stock options, firms are more inclined to undertake acquisitions and divestitures. Similarly, Lerner and Wulf (2007) find that long-term incentives are positively associated with R&D performance. Kim et al. (2017) show that equity-linked incentives motivate managerial risk-taking as they improve the sensitivity of CEO wealth to shock return volatility. Similarly, Bhaskar et al. (2023) report that a significant proportion of long-term financial reward incentivizes the CEO to act in the organization's best interests and make decisions that enhance firm performance. Therefore, we expect that when the CEO's compensation is tied to the company's performance, they will be more willing to create greater value for the company. Thus, we propose the following hypothesis:

Hypothesis 3 Other things equal, return on innovation investment will be higher when the CEO has a higher ratio of long-term compensation.

The moderating effect of CEO power

CEO power is magnified when the CEO is also the chairperson. If the two roles are separate, agency issue can be resolved; however, this may promote role ambiguity and uncertainty (Finkelstein and D'aveni 1994). This scenario increases the CEOs' perceived employment risk, thereby reducing R&D investment. By contrast, CEO duality provides CEOs with increased authority, thus diminishing ambiguity and uncertainty, leading to more R&D spending (Finkelstein and D'aveni 1994; Wiseman and Gomez-Mejia 1998; Zona 2016). Therefore, when a CEO is also the chairperson, there is greater discretion in leveraging investment decisions to drive firm performance. As aforementioned, CEOs may consider the capitalization process of knowledge stocks as an optimal chance to not only safeguard their wealth but also bolster their job stability and social standing (Lewellyn and Muller-Kahle 2012). Moreover, successful innovation can significantly broaden a firm's existing product-market portfolio and scale. Leading such an enlarged, intricate, and diversified firm is likely to enhance the CEO's authority and sway over the organization and its stakeholders (Baker et al. 2012). Therefore, we propose the following hypothesis:

Hypothesis 4a Other things equal, return on innovation investment will be higher for firms managed by more powerful CEOs.

We conjecture that CEO duality may negatively affect knowledge capitalization. Following traditional agency theory, CEOs tend to prioritize personal incentives and empire-building rather than higher return on innovation investment for the benefit of their stakeholders and shareholders (Jensen 1993; Young 1990). Under these conditions, the board should remain independent of management to limit managerial entrenchment (Jensen and Meckling 1976). Otherwise, a dual-board leadership structure may negatively affect performance by weakening the board's ability to effectively oversee management (Jensen 1993). Therefore, we propose the following hypothesis:

Hypothesis 4b Other things equal, return on innovation investment will be lower for firms managed by more powerful CEOs.

Data and methods

We combine data from three sources. Data on innovation output and quality are obtained from the EPO's Worldwide Patent Statistical Database (PATSTAT, 2021 Spring Edition). In contrast to the widely used National Bureau of Economic Research (NBER) patent data, which only include patents granted by the USPTO, PATSTAT contains bibliographic information on more than 100 million patent applications and awards from over 100 patent offices around the world.[4] We follow the patent literature and focus only on utility patents (Levine et al. 2017).[5] To obtain data on firm financial characteristics, we rely on Refinitiv. We collect CEO characteristic data from BoardEx.

To construct the data used in this study, we merge the patent data from PATSTAT with firm financial characteristics from Refinitiv using the company's name and address.[6] We then collect CEO characteristic variables from the BoardEx database using the firms' ID on Refinitiv.

Following Hanauer (2014), we restrict our sample to (1) both active and inactive companies across 23 developed countries/regions and 21 emerging countries/regions and (2) companies located and listed in the domestic country. Additionally, we exclude the most recent three years of data to mitigate potential truncation bias, because the time lag between patent filing and grant approval can vary significantly among different patent offices (Dass et al. 2017; Zuniga et al. 2009). The start year of the sample is 1999, aligning the patent and financial data with the BoardEx sample.

The final sample includes 19,070 firm-year observations from 7230 firms between 1999 and 2017.

[4] Although many studies on innovation use USPTO data on the assumption that all important patents around the world are also enforced in the US, which is the largest technology consumption market (Hsu et al. 2014), Chang et al. (2015) contend that many emerging countries do not file patent applications with the USPTO. Thus, using USPTO data may underestimate patent stocks by non-US firms.

[5] In PATSTAT, patents are divided into patent of invention, utility model and design patents. A utility patent, commonly known as "patent of invention", is defined as the invention of a novel and valuable process, machine, manufacture, material composition, or a beneficial enhancement of these (USPTO 2016).

[6] We do not report detailed matching processes in order to conserve space. The algorithms are available upon request.

Knowledge stock

To measure the patent stock for each company, $PatentStocks_{i,t-1}$, we sum the number of patents a firm is granted prior to and up to a given year $t-1$ (Arora et al. 2021a). The number of patents is calculated at the family level, which means that an invention is considered only once regardless of how many applications are made for it (Levine et al. 2017).[7]

To represent the R&D stock for each firm, $R\&DStock_{i,t-1}$, we measure the cumulative R&D investment of companies until year $t-1$. This is calculated using a perpetual inventory method with a 15 percent depreciation rate (Hall et al. 2005).

CEO characteristics

Following the literature, we focus on observable (tangible) CEO characteristics (Görts 2016). Tangible CEO characteristics are inherently more objective and accessible, making them reliable indicators of their cognitive frameworks, thereby facilitating the formulation of predictions regarding strategic actions (Hambrick 2007; Hsu et al. 2013). Furthermore, compared with intangible CEO characteristics (e.g., overconfidence and optimism), focusing on tangible attributes allows us to tap into a much larger sample of companies and CEOs (Görts 2016; Manner 2010).

We consider CEO characteristics by including $CEOAge_{i,t-1}$, which is the age of the CEO of firm i in year $t-1$ (He and Hirshleifer 2022); $CEODuality_{i,t-1}$, which is a binary variable with a value of "1" if firm i's CEO also serves as the chairperson of the board of directors in year $t-1$ and "0" otherwise (Sariol and Abebe 2017)[8]; and $CEOLongCompensationRatio_{i,t-1}$, which is the ratio of long-term compensation to total compensation in year $t-1$.

Variable descriptions are presented in Table 10.

Analysis

Descriptive statistics

Table 1, Panel A provides descriptive statistics for the main variables used in this study. The average (median) R&D expenditure is 0.2 (0.02) million US dollars per year. The median number of patent applications per year is 2. The mean number of applications is considerably higher (43.36). The average CEO age is 56, ranging from 27 to 96. Approximately, 45% of CEOs also serve as chairman of the board of directors. On average, 64% of CEOs' compensation comes from long-term compensation, such as total stock, option awards and value of long-term incentive plans.

Market value equation

Following previous studies (Bloom et al. 2013; Jaffe 1986; Arora et al. 2021a), we obtain Equation (Eq.) (2), after taking the logarithms of both sides of Eq. (1).

[7] This is because patents are territorial. When an invention is filed for patent protection in one country, it must be separately filed in another country since patent laws and examination procedures differ from one jurisdiction to another. If the measurement of innovation output relies on the count of patent applications, whether they pertain to a single invention or not, it is more likely to assess a firm's capacity to submit patent applications rather than its effectiveness in generating novel knowledge.

[8] Previous literature, including Finkelstein (1992), Finkelstein et al. (2009), and Krause et al. (2014), has identified that CEO duality reflects reduced board oversight and increased CEO power.

Table 1 Summary statistics for main variables

Variable name	No. of obs	Mean	Std. dev	Min	Median	Max
Panel A Summary statistics for main variables						
$Tobin's\ Q_t$	19,012	2.25	3.35	− 197.43	1.63	125.18
$R\&DStock(\$mm)_{t-1}$	19,070	.98	3.88	0	.07	61.67
$R\&DExpenditure(\$mm)_{t-1}$	19,070	.2	0.79	0	.02	16.08
$PatentStock_{t-1}$	19,070	805.43	4318.50	0	26	102,362
$PatentCounts_{t-1}$	19,070	43.36	227.48	0	2	5930
$Assets(\$mm)_{t-1}$	19,025	18.52	101.90	0	1.13	2949.31
$CEOAge_{t-1}$	16,880	56.18	7.74	27	56	96
$CEOLongCompensationRatio_{t-1}$	5025	.64	0.34	0	.78	1
$CEODuality_{t-1}$	19,070	.45	0.50	0	0	1
Panel B Pairwise correlation						
(1) $LN(Tobin's\ Q_t)$	1.00					
(2)$PatentStocks_{t-1}/Aessts_{t-1}$	0.087***	1.00				
(3)$R\&DStock_{t-1}/Aessts_{t-1}$	0.229***	0.369***	1.00			
(4)$CEOAge_{t-1}$	− 0.115***	0.033***	− 0.024***	1.00		
(5) $CEOLongCompensationRatio_{t-1}$	0.129***	− 0.077***	− 0.094***	0.033**	1.00	
(6)$CEODuality_{t-1}$	− 0.044***	− 0.030***	− 0.076***	0.198***	0.114***	1.00

Detailed definitions of variables are provided in Table 10

$$LnValue_{i,t} = Lnq_t + \sigma LnAssets_{i,t} + \sigma Ln\left(1 + \gamma\left(\frac{Knowledge_{i,t}}{Assets_{i,t}}\right)\right) \tag{2}$$

In this formulation, γ measures the shadow value of knowledge assets relative to the tangible assets of the firm, and $\sigma\gamma$ measures their absolute value (Hall et al. 2005). If the value function exhibits constant returns to scales (as it does approximately in the cross section), then $\sigma = 1$. Thus, we can move $LnAssets_{i,t}$ to the left side of the equation. The model becomes

$$Ln(Tobin'sQ_{i,t}) = Ln\left(\frac{Value_{i,t}}{Assets_{i,t}}\right) = Lnq_t + Ln\left(1 + \gamma\left(\frac{Knowledge_{i,t}}{Assets_{i,t}}\right)\right) \tag{3}$$

where $\frac{Value_{i,t}}{Assets_{i,t}}$ is also known as Tobin's Q, which is defined as the ratio of the market value to the replacement cost of firm i in year t (Hall et al. 2007). Following Bloom et al. (2013), we approximate $Ln\left(1 + \gamma\left(\frac{Knowledge_{i,t}}{Assets_{i,t}}\right)\right)$ by $\varnothing\frac{Knowledge_{i,t}}{Assets_{i,t}}$. it is more computationally convenient when including fixed effects. We parameterize Lnq_t as follows (Bloom et al. 2013):

$$Lnq_t = \alpha_0 + \alpha_3 Controls_{i,t} + FEs + \varepsilon_{i,t} \tag{4}$$

Finally, consistent with previous literature (Arora et al. 2021a; Bloom et al. 2013), the basic market value equation is as follows[9]:

[9] Consistent with the previous literature (e.g., Bloom et al. 2013; Arora et al. 2021a), we do not include the lagged Tobin's Q in this equation. Introducing a dynamic model, that is including the lag of Tobin's Q as an independent variable, would introduce a bias in the regression as Tobin's Q is typically a persistent variable over time.

Table 2 Pooled regression

Variable name	$LN(Tobin's\ Q_t)$			
	(1)	(2)	(3)	(4)
$PatentStocks_{t-1}/Assets_{t-1}$	23.67***	9.940***	10.77***	23.67***
	[3.6346]	[2.0938]	[2.0608]	[3.6350]
$R\&DStock_{t-1}/Assets_{t-1}$	0.0120*	0.0606***	0.0540***	0.0120*
	[0.0047]	[0.0044]	[0.0044]	[0.0047]
_cons	0.940***	0.969***	1.011***	0.77
	[0.0855]	[0.1566]	[0.1628]	[0.4599]
Year FEs	Yes	Yes	Yes	Yes
Firm FEs	Yes			Yes
Industry FEs		Yes	Yes	Yes
Country FEs			Yes	Yes
No. of observation	19,070	19,067	19,067	19,067
Adj. R^2	0.6695	0.3442	0.3661	0.6694

***, **, * refer to the significant level at 1%, 5%, and 10%. This table reports Pooled regression of Tobin's Q on R&D and patent stocks. Column (1) controls firm fixed effects and year dummies; column (2) controls industry fixed effects and year; column (3) controls industry fixed effects, country fixed effects and year dummies; column (3) controls firm fixed effects, industry fixed effects, country fixed effects and year dummies. The table reports coefficients and standard error in parentheses. Detailed definitions of variables are provided in Table 10

$$Ln(Tobin'sQ_{i,t}) = \alpha_0 + \alpha_1 \frac{Patentstocks_{i,t-1}}{Assets_{i,t-1}} + \alpha_2 \frac{R\&Dstock_{i,t-1}}{Assets_{i,t-1}} + \alpha_3 Controls_{i,t-1} + FEs + \varepsilon_{i,t-1} \quad (5)$$

where $Patentstocks_{i,t-1}$ is constructed by summing the number of patents a firm i owns prior to and up to a given year $t-1$ (Arora et al. 2021a). $R\&Dstock_{i,t-1}$ is calculated using the perpetual inventory method with a 15 percent depreciation rate (Hall 1990; Hall et al. 2005). $Controls_{i,t-1}$ represents board characteristics (i.e.,$BoardSize_{i,t-1}$, $BoardGenderRatio_{i,t-1}$, $BoardIndependence_{i,t-1}$), FEs refer to fixed effects.

Table 2 reports the Pooled regression results of Eq. (5). In Table 2, Column 1, we estimate Eq. (5) using year and firm fixed effects.[10] In Column 2, we replace firm fixed effects (FEs) with industry FEs; in Column 3, we add country Fes; and in Column 4, we include year, firm, industry and country FEs. Across, all specifications, we find that the ratio of patent stock to total assets increases Tobin's Q. This result is highly statistically significant (coefficient = 23.67, $p < 0.01$). Equally, R&D stock to total assets has a positive effect on Tobin's Q. Economically, a 1-unit rise in the R&D stock to total assets ratio results in an increase of Tobin's Q by 1.2 percent.

Overall, using an international sample, the results in Table 2 support *H1* and confirm previous literature that knowledge stock has a significantly positive effect on Tobin's Q (Arora et al. 2021a; Hall et al. 2007, 2005). We now focus on the moderating effects of CEO characteristics.

[10] The Hausman test rejects the null hypothesis that the random effects model is appropriate (test statistic 209.26, p-value < 0.01).

The moderating effect of CEO characteristics

In Columns 1 and 2 of Table 3, we investigate *H2* that, other things being equal, the return on innovation investment will be higher for firms managed by younger CEOs. To this end, we control for year- and firm-fixed effects to account for possible time- and firm-invariant heterogeneity, respectively.

As hypothesized, the effect of knowledge stock on Tobin's Q is significantly higher for younger CEOs than for older CEOs. In Column 1 of Table 3, the coefficient of knowledge stock is 49.18 ($p < 0.01$) and the coefficient of R&D stock to total assets is 0.0450 ($p < 0.01$). For firms managed by older CEOs, knowledge stock is 15.06 ($p < 0.10$), and R&D stock to total assets is 0.0161 ($p < 0.01$). Economically, Tobin's Q for firms managed by younger CEOs is three times more sensitive to knowledge stock that is 3.26 times higher than that for firms managed by older CEOs. The equivalent figure of R&D stock to total assets is 2.79, indicating that younger CEOs have a better capacity to absorb the stock of new knowledge obtained from R&D investments.

In Table 4, we investigate *H3* that other things being equal, return on innovation investment will be higher when the CEO has a higher ratio of long-term compensation. To this end, we separate the entire sample into two groups using the median value of the ratio of CEO long-term compensation to the total compensation in year $t-1$.

The results in Table 4 present a sharp contrast in the ability of firms to exploit knowledge stock and R&D intensity depending on the compensation structure of the CEO. For firms managed by CEOs with a relatively short compensation structure, the coefficient of knowledge stock is negative and significant (coefficient $= -45.91$, $p < 0.10$). Equally, the coefficient of R&D intensity is also negative and highly significant (coefficient $= -0.100$, $p < 0.1$). For firms managed by CEOs with relatively long-term compensation structures, both the knowledge stock (coefficient $= 165.7$, $p < 0.10$) and R&D intensity (coefficient $= 0.362$, $p < 0.01$) coefficients are positive and significant.

Table 3 The effect of CEO demographic characteristics on knowledge capitalization

Variable name	$LN(Tobin'sQ_t)$	
	$CEOAge_{t-1}$	
	(1)	(2)
	Young	Old
$PatentStocks_{t-1}/Assets_{t-1}$	49.18***	15.06*
	[11.5520]	[5.8781]
$R\&DStock_{t-1}/Assets_{t-1}$	0.0450***	0.0161**
	[0.0111]	[0.0059]
_cons	0.769***	0.609**
	[0.1855]	[0.2097]
Year FEs	Yes	Yes
Firm FEs	Yes	Yes
No. of observation	7831	9049
Adj. R^2	0.6957	0.7358

***, **, * refer to the significant level at 1%, 5%, and 10%. This table reports Pooled regression of Tobin's Q on R&D and patent stocks. In Column (1) and Column (2), the entire sample is separated based on the medium age of CEO. All columns control firm fixed effects and year dummies. The table reports coefficients and standard error in parentheses. Detailed definitions of variables are provided in Table 10

Table 4 The effect of CEO compensation structure on knowledge capitalization

Variable name	$LN(Tobin's\ Q_t)$	
	$CEOLongCompensationRatio_{t-1}$	
	(1)	(2)
	Low	High
$PatentStocks_{t-1}/Assets_{t-1}$	−45.91*	165.7*
	[18.5555]	[72.2603]
$R\&DStock_{t-1}/Assets_{t-1}$	−0.100***	0.362***
	[0.0271]	[0.0819]
_cons	0.676***	2.429***
	[0.1337]	[0.2867]
Year FEs	Yes	Yes
Firm FEs	Yes	Yes
No. of observation	2513	2512
Adj. R^2	0.7144	0.739

***, **, * refer to the significant level at 1%, 5%, and 10%. This table reports Pooled regression of Tobin's Q on R&D and patent stocks. In Column (1) and Column (2), the entire sample is separated based on median value of ratio of CEO long-term compensation to total compensation. All columns control firm fixed effects and year dummies. The table reports coefficients and standard error in parentheses. Detailed definitions of variables are provided in Table 10

Table 5 The effect of CEO power on knowledge capitalization

Variable name	$LN(Tobin's\ Q_t)$	
	$CEODuality_{t-1}$	
	(1)	(2)
	Chairperson = 0	Chairperson = 1
$PatentStocks_{t-1}/Assets_{t-1}$	27.55***	50.04***
	[4.3270]	[12.1485]
$R\&DStock_{t-1}/Assets_{t-1}$	0.00873	0.0143
	[0.0065]	[0.0098]
_cons	0.904***	0.895***
	[0.1667]	[0.1910]
Year FEs	Yes	Yes
Firm FEs	Yes	Yes
No. of observation	10,569	8501
Adj. R^2	0.658	0.7395

***, **, * refer to the significant level at 1%, 5%, and 10%. This table reports Pooled regression of Tobin's Q on R&D and patent stocks. In Column (1) and Column (2), the entire sample is separated based on CEO duality. All columns control firm fixed effects and year dummies. The table reports coefficients and standard error in parentheses. Detailed definitions of variables are provided in Table 10

Finally, in Table 5, we investigate *H4a* and *H4b* that other things equal, returns on innovation investment will be higher (lower) for firms managed by more (less) powerful CEOs. We use a CEO duality dummy to measure CEO power. To this end, we separate the entire sample based on whether a CEO concurrently holds the position of board chairperson. This result generally confirms *H4a*. The coefficient of knowledge stock when the CEO is also a board member is positive and highly significant (coefficient = 50.04, $p < 0.01$). When the CEO is not the chairperson of the board, the coefficient of knowledge stock is 1.8 times smaller (coefficient = 27.55, $p < 0.01$).

This result is consistent with Boyd's (1995) perspective on the advantages of CEO duality amid high environmental uncertainty. CEO duality facilitates a cohesive command structure and the rapid decision-making capabilities essential for effectively navigating uncertainty (Boyd 1995). It is evident that there are multiple stages and a significant degree of unpredictability in turning knowledge assets into commercial products that can provide a profit (Mansfield et al. 1977; Coad and Rao 2008). This result is also in line with He and Wang (2009) and Brickley et al. (1997), who find that the separation of the CEO and board chair roles increases the cost of CEO-chair information asymmetries, which are exacerbated when managing the company necessitates utilizing substantial knowledge assets.

Robustness test

In this section, we test the robustness of the empirical results by including different control variables and using a different model.

First, we assess our findings by incorporating the different control variables in Table 6. In Panel A, we control for board characteristics (i.e., board size, ratio, and independence) to gauge the significance of firm corporate governance in influencing the correlation between corporate innovation and firm performance (Balsmeier et al. 2014; Cumming and Leung 2021; Griffin et al. 2021; Robeson and O'Connor 2013). In addition, our regression includes firm, industry, country, and year fixed effects. Panel B includes board characteristics, firm, industry-year, and country-year fixed effects. After considering these factors, we obtain similar results (Tables 3, 4, and 5). For example, in Panel A, the coefficients of patent stock (coefficient = 49.07, $p < 0.01$) and R&D stock (coefficient = 0.0465, $p < 0.01$) in Column 1 (young CEO group) are larger than those of patent stock (coefficient = 13.18, $p < 0.1$) and R&D stock (coefficient = 0.0167, $p < 0.05$) in Column 2 (old CEO group).

Overall, the results in Table 6 confirm our baseline finding that firms with younger and more powerful CEOs and a higher ratio of long-term compensation to total compensation achieve higher Tobin's Q.

In addition, we test if our results hold under an alternative specification. To this end, following Hall et al. (2007, 2005), we estimate the market value of stock knowledge using nonlinear least squares. We estimate Eq. (1) as follows:

$$Ln(Tobin's\ Q_{i,t}) = Lnq_t + Ln\left(1 + \gamma_1 \frac{R\&Dstock_{i,t-1}}{Assets_{i,t-1}} + \gamma_2 \frac{Patentstock_{i,t-1}}{Assets_{i,t-1}}\right) + FEs + \varepsilon_{i,t} \tag{6}$$

Table 7 reports the nonlinear regression results of Eq. (6). In Table 7, Columns 1 and 2, we find that the coefficient of patent stock (R&D stock) on Tobin's Q for firms managed by younger (older) CEOs is 1.12 times (1.05 times) higher than that for firms managed by older (younger) CEOs. Although R&D stocks have a higher effect on Tobin's Q in Table 6, Column 2 than in Column 1 (i.e., coefficient = 0.426, $p < 0.05$; coefficient = 0.404, $p < 0.05$), its sensitivity to Tobin's is smaller than the knowledge stock to Tobin's Q in Column 1 (i.e., 1.05 times; 1.12 times). Thus, the nonlinear regression results support *H2*.

Table 6 The effect of CEO characteristics on knowledge capitalization

Variable name	$LN(Tobin's\ Q_t)$					
	$CEOAge_{t-1}$		$CEOLongCompensationRatio_{t-1}$		$CEODuality_{t-1}$	
	(1)	(2)	(3)	(4)	(5)	(6)
	Young	Old	Low	High	Chairperson = 0	Chairperson = 1
Panel A						
$PatentStocks_{t-1}/Assets_{t-1}$	49.07***	13.18*	−44.13*	157.5*	26.90***	47.96***
	[12.0036]	[5.8813]	[18.6549]	[73.7367]	[6.3681]	[12.3178]
$R\&DStock_{t-1}/Assets_{t-1}$	0.0465***	0.0167**	−0.121***	0.326***	0.00861	0.0106
	[0.0113]	[0.0059]	[0.0269]	[0.0841]	[0.0068]	[0.0098]
_cons	−0.204	0.768	−0.265	4.289***	2.930*	−0.864
	[0.8004]	[0.4117]	[0.5614]	[0.7678]	[1.2213]	[1.1994]
Board characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes	Yes	Yes
Firm FEs	Yes	Yes	Yes	Yes	Yes	Yes
Industry FEs	Yes	Yes	Yes	Yes	Yes	Yes
Country FEs	Yes	Yes	Yes	Yes	Yes	Yes
No. of observation	7601	8875	2491	2491	8367	8329
Adj. R^2	0.7001	0.7398	0.7241	0.7412	0.687	0.744
Panel B						
$PatentStocks_{t-1}/Assets_{t-1}$	49.37***	12.73	95.77	616.8***	22.11**	41.15*
	[13.4725]	[6.6201]	[52.2812]	[137.6553]	[7.1433]	[17.5612]
$R\&DStock_{t-1}/Assets_{t-1}$	0.0433**	0.0224**	−0.0251	0.543***	0.0133	0.0233
	[0.0135]	[0.0068]	[0.0657]	[0.1110]	[0.0080]	[0.0131]
_cons	−0.979	1.250**	0.436	−0.969*	0.486	0.125
	[0.8746]	[0.4171]	[0.4690]	[0.4484]	[0.5470]	[0.5081]

Table 6 (continued)

Variable name	***LN(Tobin's Q_t)***					
	CEOAge$_{t-1}$		***CEOLongCompensationRatio$_{t-1}$***		***CEODuality$_{t-1}$***	
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	Young	**Old**	**Low**	**High**	**Chairperson = 0**	**Chairperson = 1**
Board characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Firm FEs	Yes	Yes	Yes	Yes	Yes	Yes
Industry-Year FEs	Yes	Yes	Yes	Yes	Yes	Yes
Country-Year FEs	Yes	Yes	Yes	Yes	Yes	Yes
No. of observation	7601	8875	2491	2491	8367	8329
Adj. R^2	0.6755	0.7192	0.7415	0.7888	0.6482	0.7258

Note: ***, **, * refer to the significant level at 1%, 5%, and 10%. This table reports Pooled regression of Tobin's Q on R&D and patent stocks. In Panel A, all columns control board characteristics (i.e.,$BoardSize_{i,t-1}$, $BoardGenderRatio_{i,t-1}$, $BoardIndependence_{i,t-1}$), firm fixed effects, industry fixed effects, country fixed effects and year fixed effects. In Panel B, all columns control board characteristics (i.e.,$BoardSize_{i,t-1}$, $BoardGenderRatio_{i,t-1}$, $BoardIndependence_{i,t-1}$), firm fixed effects, industry-year fixed effects and country-year fixed effects. In Column (1) and Column (2), the entire sample is separated based on the medium age of CEO. In Column (3) and Column (4), the entire sample is separated based on median value of ratio of CEO long-term compensation to total compensation. In Column (5) and Column (6), the entire sample is separated based on CEO duality. Detailed definitions of variables are provided in Table 10

In Columns 3 and 4 of Table 7, although the coefficients of knowledge stocks are insignificant, the coefficient of R&D intensity in Column 5 is significantly lower than that in Column 6 (i.e., coefficient = 0.498, $p < 0.01$; coefficient = 0.914, $p < 0.01$). In this case, the robustness test supports *H3*.

In Columns 5 and 6 of Table 7, the non-linear regression results support *H4a*. While the coefficient of knowledge stock is positive but insignificant (coefficient = 7.241, $p > 0.1$), the coefficient of knowledge stock is positive and significant (coefficient = 95.77, $p < 0.01$). In addition, the coefficient of R&D stock is smaller when firms are managed by lower-power CEOs (coefficient = 0.429, $p < 0.01$; coefficient = 0.501, $p < 0.01$).

Effect of CEO compensation

In this section, we analyze the impact of the CEO compensation structure on a firm's knowledge capitalization process. We first consider the trade-off between short- and long-term compensation, and then consider the long-term effect of the ratio of CEO long-term compensation to total compensation.

In Table 8, we show the effect of CEO compensation on knowledge capitalization. We find that firms with higher levels of compensation, whether in the short or long term, generally exhibit increased market value. In Panel A, we observe that the coefficients of patent stock (coefficient = 207.8, $p < 0.05$) and R&D stock (coefficient = 0.214, $p < 0.10$) in Column 2 (high CEO Short Compensation group) are larger than those of patent stock (coefficient = 40.11, $p < 0.10$) and R&D stock (coefficient = −0.0449, $p > 0.10$) in Column 1 (low CEO Short Compensation group). This finding supplements our baseline finding (Table 4) that companies with a greater proportion of long-term compensation relative to total compensation are likely to generate a higher market value. Further, these findings indicate that while both long- and short-term compensation motivate CEOs to engage in the knowledge capitalization process, long-term compensation proves to be a more potent incentive for their participation.

In Table 9, we investigate the long-term effects of the CEO's compensation ratio on a firm's knowledge capitalization process. Each year, we observe positive coefficients for patent and R&D stock within the group with a high CEO long-term compensation ratio. For example, in Panel A, we display the positive coefficients of patent and R&D stock in Column 2 (coefficient of patent stock = 101.4, $p > 0.10$; coefficient of R&D stock = 0.336, $p < 0.01$). However, these positive coefficients are not always significant (e.g., the coefficient of patent stock in Column 6 = 102.2, $p > 0.10$; the coefficient of R&D stock in Column 6 = 0.125, $p > 0.10$). In this case, we argue that in the long run, firms with a higher CEO long-term compensation ratio may not yield a significantly positive effect on a firm's knowledge capitalization process. Furthermore, we consistently observe negative and significant coefficients for patent and R&D stock within the group characterized by a low CEO long-term compensation ratio (e.g., in Panel A, the coefficient of patent stock in Column 1 = −78.10, $p < 0.01$; the coefficient of R&D stock in Column 1 = −0.129, $p < 0.01$). Thus, companies with a lower CEO long-term compensation ratio tend to exhibit a notably negative impact on the conversion of knowledge stock into market value. This means that, over the long term, companies cannot rely solely on increasing CEOs' long-term compensation to drive the transformation of knowledge capital.

Table 7 Nonlinear regression

Variable name	$LN(Tobin's\ Q_t)$					
	$CEOAge_{t-1}$		$CEOLong\ CompensationRatio_{t-1}$		$CEODuality_{t-1}$	
	(1)	(2)	(3)	(4)	(5)	(6)
	Young	Old	Low	High	Chairperson = 0	Chairperson = 1
$PatentStocks_{t-1}/Assets_{t-1}$	77.38***	68.81***	3.148	− 102.8	7.241	95.77***
	[22.3567]	[17.2228]	[18.2613]	[69.7248]	[6.4447]	[21.0023]
$R\&DStock_{t-1}/Assets_{t-1}$	0.404***	0.426***	0.498***	0.914***	0.429***	0.501***
	[0.0226]	[0.0216]	[0.0451]	[0.0748]	[0.0179]	[0.0265]
_cons	0.681***	0.556***	0.447***	0.751***	0.649***	0.584***
	[0.0194]	[0.0160]	[0.0364]	[0.0295]	[0.0164]	[0.0177]
Year FEs	Yes	Yes	Yes	Yes	Yes	Yes
Firm FEs	Yes	Yes	Yes	Yes	Yes	Yes
No. of observation	7831	9049	2513	2512	10,569	8501
Adj. R^2	0.1493	0.1328	0.123	0.1708	0.1606	0.1403

***, **, * refer to the significant level at 1%, 5%, and 10%. This table reports Nonlinear regression of Tobin's Q on R&D and patent stocks. In Column (1) and Column (2), the entire sample is separated based on the medium age of CEO. In Column (3) and Column (4), the entire sample is separated based on median value of ratio of CEO long-term compensation to total compensation. In Column (5) and Column (6), the entire sample is separated based on CEO duality. All columns control firm fixed effects and year fixed effects. The table reports coefficients and standard error in parentheses. Detailed definitions of variables are provided in Table 10

However, reducing a CEO's long-term compensation is not a viable option, as it diminishes the level of knowledge capital transformation within the company.

Conclusion and implications

Belo et al. (2022) report that knowledge capital's contribution to firm value increased significantly from 25% in the 1970s to 45% in the 2010s. Therefore, what impact does a firm's ability to maximize the effect of knowledge capital have on firm value? Drawing on insights from upper echelons, agency, and behavioral agency theories, we conjecture that CEO characteristics play a crucial role in enabling firms to take full advantage of knowledge stock.

We demonstrate that CEO characteristics play an important moderating role in a firm's ability to capitalize on new knowledge. We show that CEO age, CEO power, and compensation structure are significant determinants of a firm's ability to convert knowledge stock into firm value. This previously unobserved heterogeneity is economically significant.

Our results highlight the importance of sound corporate governance for aligning CEO incentives with firm objectives. In particular, we show that remuneration incentives that align the long-term interests of the CEO with the long-term profitability of the firm enhance the firm's ability to maximize knowledge stock and increase R&D intensity.

Table 8 The effect of CEO short-term and long-term compensation on knowledge capitalization

Variable name	$LN(Tobin'sQ_t)$			
	$CEOShortCompensation_{t-1}$		$CEOLongCompensation_{t-1}$	
	(1)	(2)	(3)	(1)
	Low	High	Low	High
Panel A				
$PatentStocks_{t-1}/Assets_{t-1}$	40.11*	207.8**	−52.40**	289.6***
	[17.5211]	[67.6267]	[19.8343]	[73.4432]
$R\&DStock_{t-1}/Assets_{t-1}$	−0.0449	0.214*	−0.0583*	0.138
	[0.0297]	[0.0879]	[0.0272]	[0.0930]
_cons	0.569***	1.507***	0.625***	1.710***
	[0.1681]	[0.1538]	[0.1392]	[0.2112]
Year FEs	Yes	Yes	Yes	Yes
Firm FEs	Yes	Yes	Yes	Yes
No. of observation	2707	2711	2500	2500
Adj. R^2	0.658	0.8022	0.6983	0.7527
Panel B				
$PatentStocks_{t-1}/Assets_{t-1}$	42.92*	176.3**	−48.72*	268.3***
	[17.4777]	[67.4558]	[19.8794]	[72.9086]
$R\&DStock_{t-1}/Assets_{t-1}$	−0.0597*	0.213*	−0.0682*	0.113
	[0.0297]	[0.0874]	[0.0273]	[0.0924]
_cons	0.14	2.560***	−1.683**	2.649***
	[0.5853]	[0.5141]	[0.6404]	[0.4797]
Board characteristics	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes
Firm FEs	Yes	Yes	Yes	Yes
Industry FEs	Yes	Yes	Yes	Yes
Country FEs	Yes	Yes	Yes	Yes
No. of observation	2706	2711	2500	2500
Adj. R^2	0.6624	0.8052	0.7003	0.7568

***, **, * refer to the significant level at 1%, 5%, and 10%. This table reports Pooled regression of Tobin's Q on R&D and patent stocks. In Panel A, all columns control firm fixed effects and year dummies. In Panel B, all columns control board characteristics (i.e.,$BoardSize_{i,t-1}$, $BoardGenderRatio_{i,t-1}$, $BoardIndependence_{i,t-1}$), firm fixed effects, industry fixed effects, country fixed effects and year dummies. In Column (1) and Column (2), the entire sample is separated based on median value of CEO short-term compensation. In Column (3) and Column (4), the entire sample is separated based on median value of CEO long-term compensation. The table reports coefficients and standard error in parentheses. Detailed definitions of variables are provided in Table 10

This study has significant managerial and practical implications. We contend that knowledge-intensive firms should establish CEO compensation structures that prioritize long-term performance and grant greater authority to CEOs. Our findings show that CEO characteristics significantly affect firm performance during the knowledge capitalization process. We show that, by aligning CEO incentives and mitigating the costs associated with CEO-chair information asymmetries, firms perform better in the process of converting stock knowledge into market value. For investor decision-making, we advise that investors and stakeholders focused on maximizing firm

Table 9 The long-term effect of $CEOLongCompensationRatio_{t-n}$ on knowledge capitalization

Variable name	$LN(Tobin's\ Q_t)$					
	n = 2		n = 3		n = 4	
	(1)	(2)	(3)	(4)	(5)	(6)
	Low	High	Low	High	Low	High
Panel A Baseline test						
$PatentStocks_{t-n}/Assets_{t-n}$	−78.10***	101.4	−148.0***	198.4*	−170.5***	102.2
	[19.9378]	[79.3720]	[20.5762]	[92.1167]	[20.3749]	[99.5930]
$R\&DStock_{t-n}/Assets_{t-n}$	−0.129***	0.336***	−0.113***	0.146	−0.106***	0.125
	[0.0267]	[0.0867]	[0.0263]	[0.0899]	[0.0254]	[0.0927]
_cons	0.691***	1.000***	0.572***	1.548***	0.653***	1.014***
	−78.10***	101.4	−148.0***	198.4*	−170.5***	102.2
Year FEs	Yes	Yes	Yes	Yes	Yes	Yes
Firm FEs	Yes	Yes	Yes	Yes	Yes	Yes
No. of observation	2261	2261	2037	2036	1824	1824
Adj. R^2	0.7336	0.7578	0.7623	0.7722	0.7859	0.7839
Panel B Robustness test						
$PatentStocks_{t-n}/Assets_{t-n}$	−78.43***	88.62	−153.0***	176.7	−177.6***	88.09
	[19.9907]	[78.9668]	[20.5508]	[91.6910]	[20.4057]	[99.1664]
$R\&DStock_{t-n}/Assets_{t-n}$	−0.135***	0.316***	−0.118***	0.127	−0.111***	0.103
	[0.0267]	[0.0864]	[0.0263]	[0.0896]	[0.0255]	[0.0923]
_cons	0.27	1.607***	−1.26	2.312***	1.449***	−0.109
	[0.5416]	[0.2925]	[0.7053]	[0.3670]	[0.3987]	[0.4010]
Board characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Year FEs	Yes	Yes	Yes	Yes	Yes	Yes
Firm FEs	Yes	Yes	Yes	Yes	Yes	Yes
Industry FEs	Yes	Yes	Yes	Yes	Yes	Yes
Country FEs	Yes	Yes	Yes	Yes	Yes	Yes
No. of observation	2261	2261	2037	2036	1824	1824
Adj. R^2	0.7351	0.7606	0.7647	0.775	0.7876	0.7862

***, **, * refer to the significant level at 1%, 5%, and 10%. This table reports Pooled regression of Tobin's Q on R&D and patent stocks. In Panel A, all columns control firm fixed effects and year dummies. In Panel B, all columns control board characteristics (i.e.,$BoardSize_{i,t-1}$, $BoardGenderRatio_{i,t-1}$, $BoardIndependence_{i,t-1}$), firm fixed effects, industry fixed effects, country fixed effects and year dummies. In Column (1) and Column (2), the entire sample is separated based on median value of $CEOLongCompensationRatio_{i,t-2}$. In Column (3) and Column (4), the entire sample is separated based on median value of $CEOLongCompensationRatio_{i,t-3}$. In Column (5) and Column (6), the entire sample is separated based on median value of $CEOLongCompensationRatio_{i,t-4}$. The table reports coefficients and standard error in parentheses. Detailed definitions of variables are provided in Table 10

performance consider CEO characteristics such as age, compensation structure, and duality. By integrating these factors into their investment decisions, firms can make more informed strategic choices to enhance their portfolios. As actionable policy recommendations, we propose that policymakers and regulators carefully weigh the influence of CEO characteristics on firms' knowledge capitalization performance when formulating corporate governance regulations.

Future research should concentrate on the role of incentives in maximizing firms' knowledge stock. We hope that our findings will encourage others to explore the

Table 10 Variable definition

Variable name	Definition	Data source
$Tobin's\ Q_{i,t}$	$Tobin's\ Q_{i,t} = \frac{Value_{i,t}}{Assets_t}$ Tobin's Q is the ratio of total market value to the total asset value of firm i in the year t.	Datastream
$R\&Dstock_{i,t-1}$	$R\&Dstock_{i,t-1}$ is the cumulative R&D investment invested by the firm i until year $t-1$. It is calculated using a perpetual inventory method with a 15 percent depreciation rate.	Datastream
$Patentstock_{i,t-1}$	$Patentstock_{i,t-1}$ is constructed by summing up the number of patents a firm i are granted prior to, and up to, a given year $t-1$.	PATSTAT
$CEOAge_{i,t-1}$	CEO's age in year $t-1$.	BoardEx
$CEOLongCompensation_{i,t-1}$	It is the ratio of long-term compensation to total compensation in year $t-1$. Long-term compensation is the total stock, option awards and value of long-term incentive plans held for CEO based on the closing stock price of the annual report date selected.	BoardEx
$CEODuality_{i,t-1}$	CEO Duality is a binary variable with a value of "1" if the CEO also serves as a chairperson of the board of directors in year $t-1$ and "0" otherwise.	BoardEx

moderating effect of corporate governance in the relationship between knowledge stock and firm value.

Appendix

See Table 10.

Abbreviations

CEOs	Chief Executive Officers
EPO	European Patent Office
Eq.	Equation
FEs	Fixed effects
NBER	National Bureau of Economic Research
PATSTAT	EPO Worldwide Patent Statistical Database
R&D	Research and Development
US	United States
USPTO	United States Patent and Trademark Office

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Not applicable.

Author contribution

Lipeng Wang and Thanos Verousis provided the primary idea and framework for this work. Lipeng Wang and Mengyu Zhang contributed to data collection and analysis, while Thanos Verousis took the lead on the manuscript writing. All authors contributed to and approved the final manuscript.

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Availability of data and materials

The data that support the findings of this study are available from the EPO Worldwide Patent Statistical Database, Refinitiv, and BoardEx. Restrictions apply to the availability of the data, which were used under a license for this study.

Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that might have influenced this study.

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