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Innovation Ambidexterity in High-Tech Startups The Role of Knowledge Integration and Digital Sensing Capabilities

Amir Hossein Taherzadeh [1*]

1. Ph.D. student in Technology Management, Department of Industrial and Technology Management, Alborz Campus, University of Tehran, Tehran, Iran

*Correspondence: e-mail: amir.taherzadeh@ut.ac.ir

Abstract

This study examined how knowledge integration and digital sensing capabilities influence innovation ambidexterity in high-tech startups through their effects on exploratory and exploitative innovation. A quantitative cross-sectional design was used to investigate relationships among knowledge integration, digital sensing capabilities, exploratory innovation, exploitative innovation, and innovation ambidexterity. Data were collected from founders, managers, and innovation leaders across high-tech startups operating in digitally intensive environments. A structured survey instrument measured all constructs using validated multi-item Likert scales covering knowledge management practices, digital sensing routines, and innovation activities. Confirmatory factor analysis was conducted to assess reliability and validity, followed by structural equation modeling to test direct and indirect effects. Model fit indices, standardized path coefficients, and bootstrap-based mediation estimates were computed to evaluate the hypothesized relationships. Knowledge integration significantly predicted exploratory innovation ($\beta = 0.29$, $p < 0.001$) and exploitative innovation ($\beta = 0.24$, $p < 0.001$), while digital sensing capabilities showed even stronger effects on exploratory innovation ($\beta = 0.41$, $p < 0.001$) and exploitative innovation ($\beta = 0.33$, $p < 0.001$). Exploratory innovation ($\beta = 0.39$, $p < 0.001$) and exploitative innovation ($\beta = 0.34$, $p < 0.001$) significantly predicted innovation ambidexterity, but neither knowledge integration nor digital sensing had significant direct effects on ambidexterity. Mediation analysis confirmed significant indirect effects for both capabilities through exploratory and exploitative innovation, with digital sensing demonstrating the strongest cumulative mediation effects ($\beta = 0.27$, $p < 0.001$). Innovation ambidexterity in high-tech startups emerges primarily through innovation processes rather than direct capability effects. Knowledge integration and digital sensing capabilities enhance ambidexterity only when translated into exploratory and exploitative innovation behaviors, highlighting the critical role of capability enactment and innovation routines in achieving simultaneous exploration and exploitation.

Keywords: Innovation ambidexterity; knowledge integration; digital sensing capabilities; exploratory innovation; exploitative innovation; high-tech startups; dynamic capabilities

1. Introduction

High-tech startups operate within environments characterized by intense volatility, rapid technological evolution, and continuous shifts in competitive dynamics. In such contexts, the ability to simultaneously pursue exploratory innovation—centered on experimentation, new knowledge discovery, and radical product advancement—and exploitative innovation—focused on refinement, optimization, and efficiency—has become foundational to sustained competitiveness. This simultaneous pursuit, known as innovation ambidexterity, is increasingly recognized as a strategic capability that enables early-stage technology firms to scale, adapt, and thrive under conditions of uncertainty. Recent studies emphasize that the rise of digital technologies, data-centric business models, and AI-enabled knowledge practices fundamentally reshape how startups develop dynamic capabilities, interact with their environments, and convert knowledge into dual innovation streams (Singh et al., 2024; Yesuf, 2024; Zhang et al., 2024).

The contemporary digital economy places unprecedented emphasis on the integration of advanced sensing technologies, intelligent decision systems, and knowledge-based resources. High-tech startups increasingly face pressure to rapidly reconfigure their knowledge structures, coordinate cross-functional teams, and deploy digital tools that allow real-time detection of market changes. Digital sensing capabilities have emerged as one of the critical enablers of organizational responsiveness, allowing firms to interpret signals from dynamic technological landscapes, predict emerging opportunities, and mitigate risks associated with disruptive competition (Hardy et al., 2024; Hua et al., 2021; Nie et al., 2022). At the same time, the capacity to integrate dispersed knowledge resources—whether originating from internal R&D routines, collaborative networks, or AI-driven knowledge management systems—serves as a foundational mechanism for converting raw information into innovation outcomes (Cai et al., 2024; Mishra & Pani, 2020; Secundo et al., 2024). As startups often operate with limited resources, high uncertainty, and fluid organizational structures, knowledge integration plays an even more substantial role in directing learning behaviors, shaping innovation strategies, and balancing exploratory and exploitative trajectories.

Digital transformation has further accelerated the need for ambidextrous innovation capabilities. The growing ubiquity of intelligent sensing technologies—including machine-learning–enhanced data analytics, digital holography, multi-sensor IoT systems, and environmental scanning algorithms—has fundamentally altered how organizations identify market signals and anticipate shifts in customer needs (Hardy et al., 2024; Hua et al., 2021; Nie et al., 2022). These tools enable startups to observe fine-grained environmental patterns and translate sensor-derived insights into strategic innovation decisions. For example, advances in digital holography and integrated sensing frameworks have proven essential for industries requiring high-precision environmental monitoring, illustrating how digital sensing influences innovation in complex settings (Hardy et al., 2024; Hua et al., 2021). Meanwhile, the integration of real-time digital knowledge into organizational routines fosters more agile responses to emerging technological disruptions (Eng et al., 2022; Xin & Li, 2024).

Parallel to digital sensing, knowledge integration practices are undergoing transformation through AI-supported systems. Studies indicate that AI-driven knowledge orchestration enhances the sustainability of startups by facilitating intelligent retrieval, recombination, and sharing of organizational knowledge (Cai et al., 2024; Jiang et al., 2024). Startups that effectively deploy AI-based knowledge management achieve greater cognitive flexibility, enabling them to transition seamlessly between exploration-oriented and exploitation-oriented innovation activities (Yesuf, 2024). These emergent practices reflect a broader shift toward dynamic knowledge ecosystems, in which internal learning structures and external collaboration networks form tightly interconnected systems (Armariena, 2024; Secundo et al., 2024). In digital economies, collaborative innovation ecosystems enhance information flow, reduce uncertainty, and support collective capability building across organizational boundaries.

Theoretical and empirical work on dynamic capabilities increasingly positions innovation ambidexterity as a core outcome of digital maturity. Digital transformation reshapes strategic, cultural, and structural dimensions of organizations, enabling them to enact dual innovation logic while navigating complex competitive landscapes (Hoessler & Carbon, 2024; Motamedimoghadam et al., 2024). As digital technologies become embedded in core business processes, they facilitate more adaptive and flexible capability configurations. Digital leadership, digital literacy, and digital dynamic capabilities jointly strengthen organizational capacity to enact ambidextrous behaviors in real time (Jiang et al., 2024; Muis, 2024; Puspadi, 2024). Research shows that leaders with high levels of digital literacy enhance innovation ambidexterity through effective knowledge re-orchestration and capability alignment, highlighting the human-centered dimension of digital transformation (Jiang et al., 2024).

Furthermore, empirical evidence suggests that startups are uniquely positioned to benefit from digital dynamic capabilities due to their flexible structures and rapid decision cycles. They integrate sensing systems and knowledge processes at earlier stages of their development, often embedding ambidextrous innovation logic into their foundational business models

(Alnashmi & Alkshali, 2023; Nofiani & Fietroh, 2023). Unlike mature firms, startups can reconfigure routines quickly as they learn from market signals, implement feedback loops, and deploy digital technologies. However, this agility also requires deliberate knowledge integration mechanisms that ensure learning coherence and prevent fragmentation of innovation efforts (Prado, 2020; Puspadi, 2024).

At the same time, the increasing complexity of digital ecosystems requires organizations to understand interactions among sensing technologies, data infrastructures, and knowledge-based operations. Business intelligence systems, enterprise resource planning tools, and big-data analytic platforms are increasingly part of the knowledge infrastructure that supports innovation ambidexterity (Lara-Pérez et al., 2024; Liao et al., 2023; Rivera & Tamayo, 2024). These infrastructures help startups identify both incremental innovation paths and radical innovation opportunities, thereby balancing dual innovation modes. Researchers have shown that big-data analytics capabilities, when effectively embedded in organizational routines, significantly contribute to dual innovation outcomes by enhancing interpretive accuracy and decision-making speed (Liao et al., 2023).

Recent advances in digital entrepreneurship also reflect the growing importance of digital opportunity sensing and market-sensing capabilities. Digital entrepreneurship ecosystems amplify knowledge flows, broaden access to real-time market intelligence, and stimulate opportunity identification—all of which facilitate ambidextrous innovation behaviors (Syed et al., 2024; Zhang et al., 2024). Startups participate in platform-based ecosystems where sensing technologies and market interaction tools rapidly cycle feedback into innovation activities. This underscores the role of digital environments in fostering both exploration through new ventures and exploitation through optimized commercialization pathways (Armariena, 2024; Saputro et al., 2024).

Additionally, digital transformations within learning environments and organizational culture contribute to enhanced innovation capacities. Continuous learning structures and digital education tools cultivate digital competence, enabling employees to contribute effectively to both exploratory and exploitative efforts (Reyes-Sánchez, 2024; Singh et al., 2024). As organizations adopt digital learning systems, they create cultures capable of absorbing new technological knowledge while retaining operational stability. Such cultures reflect an integrated approach to dynamic capability development, where both learning ambidexterity and innovation ambidexterity co-evolve (Nofiani & Fietroh, 2023; Yesuf, 2024).

Knowledge-based dynamic capability frameworks further emphasize that knowledge practices and microfoundations—such as sensing, seizing, and reconfiguring—are central to achieving dual innovation performance (R et al., 2021; Secundo et al., 2024). This perspective aligns with findings showing that sensing capabilities linked to digital signals improve strategic foresight, increase organizational agility, and support adaptive decision-making in high-uncertainty environments (Hardy et al., 2024; Nie et al., 2022). These microfoundations are especially relevant in entrepreneurial contexts where rapid learning and dynamic adjustments determine survival and growth trajectories.

Human factors also remain central in shaping these innovation outcomes. Studies highlight that employees' digital skills, perceptions, and learning behaviors significantly influence the firm's ability to balance exploration and exploitation (Muis, 2024; Tingey, 2024). Digital leadership plays a meaningful role in guiding cultural alignment, fostering experimentation, and ensuring structured knowledge sharing across teams (Hoessler & Carbon, 2024; Puspadi, 2024). Further, advanced professional training, such as in mathematics for digital signal processing, strengthens workforce competencies essential for engaging with emerging sensing technologies (Klochko et al., 2024).

Altogether, the literature reveals a growing intersection between digital sensing capabilities, knowledge integration practices, and innovation ambidexterity. Startups operating in technology-intensive sectors must not only develop robust sensing mechanisms but must also integrate and orchestrate knowledge effectively to convert environmental data into meaningful innovation outcomes. However, despite substantial conceptual advancements, empirical evidence specifically exploring how these capabilities jointly shape innovation ambidexterity in high-tech startups remains limited, particularly within rapidly digitalizing economies.

Therefore, the aim of this study is to examine how knowledge integration and digital sensing capabilities influence innovation ambidexterity in high-tech startups.

2. Methods and Materials

This study employed a quantitative, cross-sectional research design aimed at examining the relationships between knowledge integration, digital sensing capabilities, and innovation ambidexterity within high-tech startups. The design was selected to capture a detailed snapshot of organizational capabilities and innovation outcomes at a specific point in time, enabling the identification of structural patterns that emerge between the predictor and outcome variables. The population consisted of high-tech startups operating in technologically dynamic environments, including sectors such as artificial intelligence, biotechnology, advanced manufacturing, and platform-based digital services. Startups were included if they had been operational for at least three years, employed a minimum of ten staff members, and demonstrated active engagement in R&D or product innovation activities. Participants were founders, senior managers, R&D leaders, and innovation directors who possessed substantial insights into their organizations' knowledge processes and digital capability development. The sample was obtained using purposive sampling to ensure that respondents represented strategic decision-making roles essential for assessing organizational capability constructs. Data collection continued until the required sample size for structural equation modeling was met, ensuring adequate statistical power for model estimation and hypothesis testing. All participants completed the survey voluntarily, and anonymity was guaranteed to support open and accurate reporting.

Data were collected using a structured, self-administered questionnaire developed based on prior validated instruments in the fields of innovation management, organizational learning, and digital capability research. The questionnaire operationalized innovation ambidexterity through items measuring both exploratory and exploitative innovation outcomes, capturing a balance between experimentation, risk-taking, incremental development, and refinement of existing products or processes. Knowledge integration was measured through items evaluating the ability of the organization to synthesize, coordinate, and combine diverse knowledge sources across teams, functions, and external partners. Digital sensing capabilities were assessed through indicators related to environmental scanning, real-time monitoring of technological trends, data-driven sensing routines, and the deployment of digital tools to identify emerging opportunities and threats. Each construct was measured using multi-item Likert-type scales to ensure precision, consistency, and internal reliability. Prior to full data collection, the questionnaire underwent a pilot test with a small group of experienced managers to confirm clarity, content validity, and response feasibility. Minor modifications were made based on pilot feedback to refine item wording, remove ambiguity, and ensure alignment between construct definitions and the operationalized measures. The finalized instrument was distributed electronically to enhance accessibility and improve response efficiency among geographically dispersed startup leaders.

Data analysis followed a multi-stage statistical procedure to ensure the robustness, reliability, and validity of the findings. The analysis commenced with data screening to address missing responses, evaluate response patterns, and confirm that data met the assumptions of multivariate analysis. Descriptive statistics were generated to characterize the sample and summarize responses across constructs. To assess measurement reliability and validity, confirmatory factor analysis was performed, allowing the evaluation of factor loadings, construct reliability, convergent validity, and discriminant validity. This step ensured that each construct accurately represented the theoretical concept it was intended to measure. Following validation of the measurement model, structural equation modeling was used to test the hypothesized relationships among knowledge integration, digital sensing capabilities, and innovation ambidexterity. Model fit indices, path coefficients, and significance levels were examined to determine the strength and direction of effects. Mediation or interaction effects were further evaluated when applicable to identify potential indirect pathways or combined influences of the predictor variables. Statistical analyses were conducted using specialized software such as SmartPLS or AMOS for structural modeling, along with SPSS for preliminary data preparation and descriptive assessment. The analytic approach enabled a rigorous examination of theoretical linkages, providing empirical evidence regarding the mechanisms through which knowledge integration and digital sensing capabilities enhance innovation ambidexterity in high-tech startups.

3. Findings and Results

The empirical results of the study are presented in this section. The findings are organized around descriptive statistics, measurement model assessment, and structural model evaluation in order to clarify how knowledge integration and digital sensing capabilities contribute to innovation ambidexterity in high-tech startups. The first set of results summarizes the descriptive statistics and bivariate correlations between the main constructs and is reported in Table 1.

Table 1. Descriptive statistics and correlations of study variables

Variable	Mean	SD	1	2	3	4	5
1. Knowledge Integration	3.84	0.62	1.00				
2. Digital Sensing Capabilities	3.91	0.64	0.52	1.00			
3. Exploratory Innovation	3.76	0.68	0.48	0.55	1.00		
4. Exploitative Innovation	3.88	0.60	0.44	0.49	0.58	1.00	
5. Innovation Ambidexterity	3.82	0.65	0.46	0.51	0.63	0.61	1.00

Note. All correlations ≥ 0.40 are significant at p < 0.01 (two-tailed). Variables were measured on a five-point Likert scale.

The descriptive statistics in Table 1 indicate that all constructs have mean values above the scale midpoint, suggesting relatively high levels of knowledge integration, digital sensing capabilities, exploratory innovation, exploitative innovation, and innovation ambidexterity among the surveyed high-tech startups. Standard deviations show a reasonable spread of responses, which is appropriate for structural analysis. The correlation matrix reveals that knowledge integration and digital sensing capabilities are positively and moderately associated with both exploratory and exploitative innovation. Furthermore, both dimensions of innovation show relatively strong correlations with innovation ambidexterity, implying that startups that simultaneously engage in exploratory and exploitative activities tend to report higher overall ambidexterity. The positive and significant correlations among the constructs provide preliminary support for the proposed relationships and justify the use of multivariate techniques to examine the structural model.

Table 2. Measurement model: standardized factor loadings

Construct	Item	Standardized Loading
Knowledge Integration	KI1	0.79
	KI2	0.83
	KI3	0.86
Digital Sensing Capabilities	DSC1	0.81
	DSC2	0.85
	DSC3	0.88
Exploratory Innovation	EXPL1	0.82
	EXPL2	0.87
	EXPL3	0.84
Exploitative Innovation	EXPT1	0.78
	EXPT2	0.83
	EXPT3	0.80
Innovation Ambidexterity	IAMB1	0.84
	IAMB2	0.89
	IAMB3	0.86

Note. All factor loadings are significant at p < 0.001.

The results in Table 2 confirm that the measurement model demonstrates satisfactory item-level properties. All standardized factor loadings exceed the commonly accepted threshold of 0.70, indicating that the items strongly reflect their associated latent constructs. The high loadings for digital sensing capabilities and innovation ambidexterity suggest particularly coherent and well-defined factors, while the loadings for knowledge integration and both forms of innovation also show strong convergence on their respective constructs. The significance of all factor loadings at $p < 0.001$ further supports the adequacy of the measurement model and provides confidence that the latent variables are being measured with appropriate precision and consistency across items.

Table 3. Reliability and convergent validity of constructs

Construct	Cronbach's Alpha	Composite Reliability	Average Variance Extracted (AVE)
Knowledge Integration	0.84	0.88	0.71
Digital Sensing Capabilities	0.87	0.91	0.77
Exploratory Innovation	0.86	0.90	0.75
Exploitative Innovation	0.83	0.87	0.69
Innovation Ambidexterity	0.89	0.93	0.80

Table 3 shows that all constructs exhibit strong internal consistency reliability, with Cronbach's alpha values ranging from 0.83 to 0.89 and composite reliability values ranging from 0.87 to 0.93, all exceeding the conventional cut-off of 0.70. The average variance extracted for each construct is above 0.60, demonstrating adequate convergent validity and confirming that a substantial portion of the variance in the indicators is accounted for by the underlying latent construct. These results collectively indicate that the measurement scales used in this study are both reliable and valid for capturing knowledge integration, digital sensing capabilities, exploratory innovation, exploitative innovation, and innovation ambidexterity in the context of high-tech startups.

Table 4. Structural model results: direct effects

Path	Standardized Coefficient (β)	t-value	p-value	Interpretation
Knowledge Integration → Exploratory Innovation	0.29	4.21	< 0.001	Supported
Knowledge Integration → Exploitative Innovation	0.24	3.65	< 0.001	Supported
Digital Sensing → Exploratory Innovation	0.41	6.02	< 0.001	Supported
Digital Sensing → Exploitative Innovation	0.33	4.87	< 0.001	Supported
Exploratory Innovation → Ambidexterity	0.39	5.48	< 0.001	Supported
Exploitative Innovation → Ambidexterity	0.34	4.92	< 0.001	Supported
Knowledge Integration → Ambidexterity	0.09	1.57	0.116	Not supported (ns)
Digital Sensing → Ambidexterity	0.07	1.28	0.200	Not supported (ns)

Note. ns = not significant at $p < 0.05$.

The structural model results reported in Table 4 provide strong support for the core theoretical relationships proposed in the study. Knowledge integration exerts significant positive effects on both exploratory and exploitative innovation, indicating that startups which are more effective at combining and coordinating dispersed knowledge resources tend to engage more intensively in both experimentation with new ideas and refinement of existing products, processes, or technologies. Digital sensing capabilities also have significant and positive impacts on exploratory and exploitative innovation, with slightly stronger coefficients than those observed for knowledge integration, suggesting that the ability to detect and interpret digital signals from the technological and market environment is particularly critical for driving innovative activities in high-tech startups. Exploratory and exploitative innovation, in turn, show significant and substantial positive effects on innovation ambidexterity, implying that a balanced portfolio of new and incremental innovation activities is central to achieving higher overall ambidexterity. By contrast, the direct paths from knowledge integration and digital sensing capabilities to innovation ambidexterity are not statistically significant, which points to the possibility that their influence on ambidexterity is transmitted primarily through exploratory and exploitative innovation rather than exerting a strong direct effect.

Table 5. Indirect effects: mediation via exploratory and exploitative innovation

Indirect Path	Indirect Effect (β)	95% Confidence Interval	p-value	Interpretation
Knowledge Integration → Exploratory → Ambidexterity	0.11	[0.06, 0.18]	< 0.001	Significant
Knowledge Integration → Exploitative → Ambidexterity	0.08	[0.03, 0.14]	0.002	Significant
Digital Sensing → Exploratory → Ambidexterity	0.16	[0.10, 0.24]	< 0.001	Significant
Digital Sensing → Exploitative → Ambidexterity	0.11	[0.05, 0.18]	< 0.001	Significant
Knowledge Integration → Exploratory & Exploitative → Ambidexterity	0.19	[0.12, 0.28]	< 0.001	Significant
Digital Sensing → Exploratory & Exploitative → Ambidexterity	0.27	[0.18, 0.36]	< 0.001	Significant

Note. Indirect effects estimated using bias-corrected bootstrapping with 5,000 resamples.

The mediation analysis results in Table 5 show that the effects of knowledge integration and digital sensing capabilities on innovation ambidexterity are fully transmitted through exploratory and exploitative innovation. All reported indirect effects are positive and statistically significant, with confidence intervals that do not include zero, confirming the mediating role of the two innovation dimensions. The indirect effects through exploratory innovation are slightly stronger than those through exploitative innovation for both knowledge integration and digital sensing capabilities, suggesting that the capacity to leverage knowledge and digital signals is particularly effective in stimulating experimentation and radical initiatives, which subsequently elevate ambidexterity. When the joint indirect effects via both exploratory and exploitative innovation are considered, digital sensing capabilities exhibit a larger cumulative effect on ambidexterity than knowledge integration, highlighting the strategic importance of advanced sensing routines and digital intelligence in high-tech startup environments. Overall, these findings indicate that innovation ambidexterity in high-tech startups is not a direct consequence of knowledge integration and digital sensing alone, but rather emerges as these capabilities are translated into concrete exploratory and exploitative innovation activities.

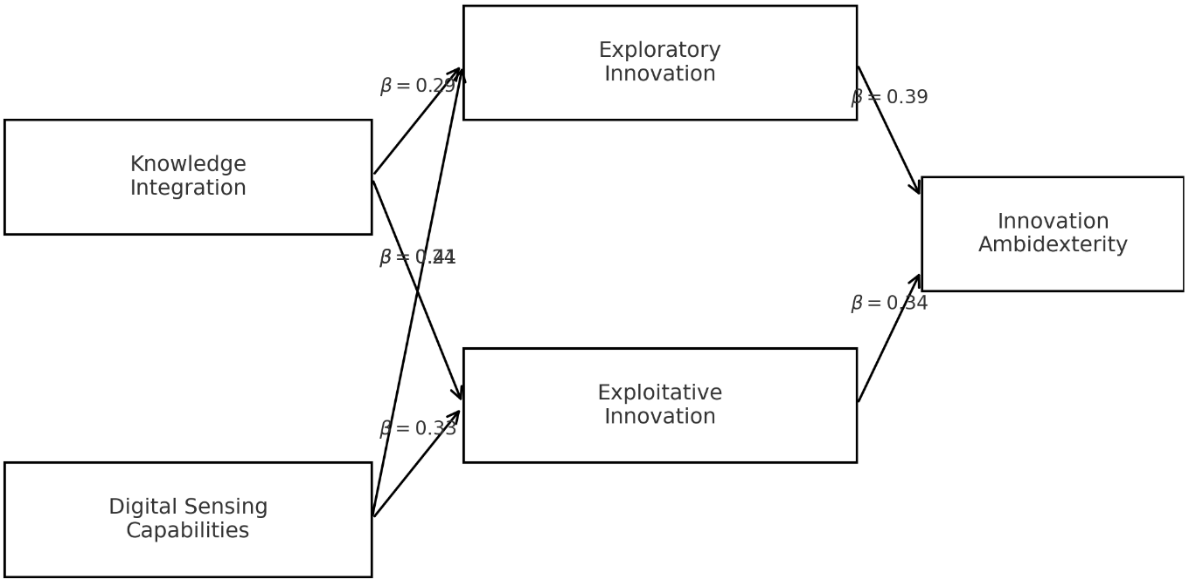

Figure 1. Model with Beta Values

4. Discussion and Conclusion

The purpose of this study was to examine the influence of knowledge integration and digital sensing capabilities on innovation ambidexterity in high-tech startups, emphasizing the mediating roles of exploratory and exploitative innovation. The findings reveal that both knowledge integration and digital sensing capabilities significantly contribute to exploratory and exploitative innovation, yet their direct influence on ambidexterity is statistically insignificant. Instead, the effects of these capabilities emerge indirectly through the two forms of innovation activity. This underscores the role of innovation processes as essential translation mechanisms through which digital and knowledge-based capabilities shape overall organizational ambidexterity. The results strongly align with recent theoretical advancements suggesting that digital capability development and knowledge practices act as microfoundations that enable firms to adapt more fluidly to technological and market shifts (Secundo et al., 2024; Yesuf, 2024).

The strong positive effect of knowledge integration on both exploratory and exploitative innovation suggests that high-tech startups benefit from orchestrating diverse knowledge sources across organizational boundaries. This result confirms earlier views that effective knowledge synthesis is a fundamental enabler of innovation capability, particularly in environments where technological complexity requires the recombination of expertise (Cai et al., 2024; Mishra & Pani, 2020). The finding aligns with research showing that knowledge practices enhance dynamic capability routines and foster resilience in digital innovation ecosystems (Armariena, 2024; Motamedimoghadam et al., 2024). From a microfoundational standpoint, knowledge integration supports both divergent thinking—enabling exploration—and efficiency gains—supporting exploitation, consistent with findings in organizational learning and ambidexterity research (Nofiani & Fietroh, 2023; Reyes-Sánchez, 2024).

Similarly, the positive influence of digital sensing capabilities on innovation processes demonstrates the increasing importance of sensing technologies and data-driven insight generation in early-stage firms. The results echo research identifying sensing as a critical component of digital dynamic capability, which enhances the firm's capacity to detect emerging opportunities and respond with appropriate innovation strategies (Nie et al., 2022; Xin & Li, 2024). The significant effect of digital sensing on exploratory innovation is consistent with studies showing that advanced sensing technologies—such as multichannel holography or AI-assisted sensing arrays—enable organizations to identify discontinuities in their environments and pursue radical innovation pathways (Hardy et al., 2024; Hua et al., 2021). At the same time, the positive effect on exploitative innovation affirms findings that digital sensing improves operational refinement through improved accuracy, prediction, and real-time feedback, supporting incremental innovation activities (Eng et al., 2022; Jiang et al., 2024).

The absence of significant direct effects of knowledge integration and digital sensing capabilities on ambidexterity provides important theoretical insight. These findings suggest that ambidexterity is not an automatic outcome of capability possession but is instead realized through innovation execution. This aligns with the broader perspective that ambidexterity is a behavioral manifestation emerging from accumulated innovation routines rather than a direct reflection of resource capabilities (Alnashmi & Alkshali, 2023; Hoessler & Carbon, 2024). Similar patterns have been documented in dynamic capability frameworks, where capability inputs require activation through organizational processes before contributing to strategic outcomes (Saputro et al., 2024; Secundo et al., 2024).

The strong mediated effects identified in the results reinforce this perspective. Exploratory and exploitative innovation act as compensatory mechanisms through which sensing and knowledge capabilities exert influence on ambidexterity. This is consistent with the notion that startups must first embed dual innovation behaviors into organizational routines before achieving the higher-level capability of ambidexterity (Nofiani & Fietroh, 2023; Prado, 2020). The significance of the indirect pathways supports earlier research emphasizing the prominent role of innovation practices as mediators between capability development and performance outcomes (Liao et al., 2023; Zhang et al., 2024).

The finding that digital sensing has a stronger cumulative indirect effect on ambidexterity than knowledge integration highlights the transformative role of digital technologies in shaping innovation processes. Startups increasingly rely on algorithmic learning, data-driven insight generation, and sensing-enhanced decision systems, enabling them to align exploration and exploitation more efficiently (Rivera & Tamayo, 2024; Syed et al., 2024). The prominence of digital sensing capabilities in the model resonates with research suggesting that sensing technologies are core triggers of strategic change and innovation reconfiguration (Hardy et al., 2024; Nie et al., 2022). Furthermore, sensing-driven innovation gains are amplified when integrated with digital literacy and digital leadership, which guide employees in transforming sensed information into actionable innovation strategies (Jiang et al., 2024; Muis, 2024).

Another important implication is the alignment of these findings with the emerging literature on digital transformation in SMEs and startups. Research shows that digital capability development, particularly sensing, market intelligence processing, and digital knowledge management, dramatically increases firms' ability to adapt to environmental turbulence and produce dual innovation outcomes (Eng et al., 2022; Kaoud & Dine, 2022; Wetering & Versendaal, 2021c). The current study reinforces these insights by illustrating that startups possessing advanced sensing capabilities produce robust exploratory outcomes while simultaneously improving operational refinement. This synergy reflects the logic of ambidexterity described in prior research on IT ambidexterity, where digital capabilities enable the simultaneous pursuit of divergent innovation pathways (Wetering & Versendaal, 2021a, 2021b).

The findings also support previous work emphasizing the significance of digital entrepreneurship ecosystems and collaborative innovation structures. These ecosystems provide startups with extended sensing opportunities, resource access, and cross-boundary knowledge flows that enhance the translation of capabilities into innovation outcomes (Armariena, 2024; Saputro et al., 2024; Singh et al., 2024). Participation in such ecosystems strengthens both exploratory search behaviors and exploitative refinements, providing environmental stability while also fostering opportunity creation.

Importantly, the study's findings align with research identifying organizational culture, digital learning environments, and continuous knowledge development as central drivers of innovation capability (Järvenpää et al., 2024; Reyes-Sánchez, 2024; Rivera & Tamayo, 2024). The indirect pathways observed in this study reinforce the notion that cultural alignment and continuous knowledge upgrading are essential for transforming sensing and integration capabilities into innovation ambidexterity. This reflects broader theoretical claims that organizational culture determines how firms interpret sensing information, share knowledge, and allocate resources across exploratory and exploitative pursuits (Muis, 2024; Puspadi, 2024).

Furthermore, the results resonate with research emphasizing the importance of mathematical, analytical, and computational skill development in enhancing the effectiveness of digital sensing systems (Hardy et al., 2024; Klochko et al., 2024). Startups relying heavily on data-driven sensing tools benefit substantially from such skill development, which improves the precision, interpretation, and strategic use of sensed information. This explains why digital sensing emerged as a stronger indirect driver of ambidexterity in the model.

The conceptual coherence between the study's findings and the literature strengthens the argument that innovation ambidexterity arises through a process of capability enactment rather than mere capability possession. Digital sensing and knowledge integration must be coupled with innovation behaviors to manifest ambidextrous outcomes, consistent with prior evidence that ambidexterity emerges from internal learning loops, digital competence development, and sustained engagement in innovation ecosystems (Nofiani & Fietroh, 2023; Secundo et al., 2024; Yesuf, 2024).

This study is based on cross-sectional data, which limits the ability to infer causality among variables over time. Although startups operate in dynamic environments, the design does not capture how capabilities and innovation behaviors evolve. The reliance on self-report instruments may introduce perceptual bias, particularly in constructs involving strategic decision processes. The sample is limited to high-tech startups, which may affect generalizability to other sectors with different innovation dynamics. Additionally, the model does not incorporate moderating factors such as organizational culture, leadership style, or environmental turbulence, which could further shape the strength of the relationships.

Future studies could employ longitudinal designs to track how digital sensing and knowledge integration influence innovation ambidexterity over time. Qualitative or mixed-method studies could reveal deeper insights into how startups operationalize sensing routines and knowledge integration in real-world innovation practices. Researchers may also investigate potential moderators, such as digital leadership, organizational structure, or ecosystem engagement. Expanding the sample to include medium or large firms, or cross-industry comparisons, could improve generalizability. Future studies might also incorporate technological turbulence or AI maturity as contextual variables shaping capability development.

Startups should prioritize investment in digital sensing technologies and analytical tools that support real-time decision-making and innovation scanning. Leaders should build organizational mechanisms for knowledge integration, such as cross-functional teams and AI-assisted knowledge systems, to enhance innovation outcomes. Managers should cultivate cultures that support both experimentation and operational refinement to strengthen ambidexterity. Firms may benefit from participating in digital innovation ecosystems to enhance sensing accuracy, access knowledge resources, and accelerate dual innovation pathways.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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