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Online Science Instruction Can Promote Adolescents' Autonomy Need Satisfaction: a Latent Growth Curve Analysis

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Abstract

This research examined the differential motivational effects of a pre-college science enrichment program delivered in both online and in-person learning formats. Using self-determination theory as a guiding framework, we hypothesized that (a) students would exhibit growth in their perceived satisfaction of needs for autonomy, competence, and relatedness, (b) online learning would be associated with greater growth in autonomy, and (c) in-person learning would be associated with greater growth in both competence and relatedness. Using a sample of 598 adolescent participants, results of latent growth curve modeling indicated that satisfaction of the three needs grew unconditionally over the course of the program. However, format type was unrelated to growth in need satisfaction. Rather, this effect was found to be conditional upon the type of science project undertaken by students: astrophysics students exhibited significantly greater autonomy growth when receiving online instruction than did biochemistry students. Our findings suggest that online science learning can be just as effective in motivating students as in-person learning provided that the learning tasks are conducive to remote instruction.

Keywords Online science learning · Inquiry-based learning · Self-determination theory · Summer Science Program · COVID-19 · Latent growth curve modeling

Science education standards emphasize the importance of engaging students in inquiry-based processes that facilitate development of scientific knowledge over processes that focus merely on acquisition of information (e.g., National Research Council, 1996). Inquiry-based learning of this nature best occurs in scientific settings (e.g., laboratories) where students can engage in authentic research (Knutson et al., 2010). Unlike

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problem-based learning activities, research-based learning activities are characterized by project outcomes that are not known in advance, and students are given greater autonomy in determining experimental procedures (Domin, 1999). The benefits of inquiry-based learning have been well documented as studies have linked this approach to improved critical thinking skills (e.g., Apedoe et al., 2006; Duran & Dökme, 2016; Gómez & Suárez, 2020) as well as increased science engagement (McConney et al., 2014) and motivation (Knutson et al., 2010). Summer-based authentic research experiences implemented at the undergraduate level have similarly enhanced students' motivation for science (e.g., Hunter et al., 2007). Investigations of the influence of authentic research experiences have rarely been extended to pre-college adolescents engaged in informal science learning. This is problematic because adolescence is a critical period for the development of enduring scientific attitudes and goals.

Summer science enrichment programs have long served the important objective of enhancing students' academic and career-related skills by supplementing the knowledge students acquire in traditional school-based settings. These summer programs have traditionally been held in face-to-face formats because they allow students to engage directly with instructional material and facilitate cooperative learning in real time. However, the onset of the COVID-19 pandemic forced many educators to adapt the way in which they deliver instructional content by shifting from more traditional in-person instructional formats to online formats. Regardless of the academic context, some content areas have lent themselves quite suitably to online learning whereas other areas do not align so readily with this format. Such misalignment is likely to be particularly problematic in the sciences, where physical engagement with instructional materials (e.g., lab equipment) is critical to learning. For meaningful science learning to occur, however, it is important that students tap into various environmental sources of academic motivation in ways that foster their basic psychological needs for autonomy, competence, and relatedness (Reeve, 2012). Learners are likely to develop greater intrinsic motivation for scientific inquiry to the extent that they feel less controlled by their instructors, more capable of conducting scientific tasks, and more interpersonally connected to both peers and educators.

In-Person Versus Online Instruction

Although it seems intuitive that in-person learning would afford more opportunity for effective dialog considering the physical proximity of instructors and learners, sharing the same physical space offers no assurance that the frequency or quality of communication will be sufficient. A key factor that determines the degree of structure needed in the learning environment relates to the extent to which learners can function autonomously. In-person learning settings are typically highly structured, as teachers traditionally assume a high degree of control over the content and delivery of instructional activities while students tend to be dependent on their teachers for direction. In contrast, online settings usually afford learners greater agency in shaping the learning process because instructors are not physically present to provide direct support.

Research conducted to date on the differential effects of online and in-person instruction has yielded mixed results. Several studies have shown no differences between the format types across a number of academic outcomes. Early meta-analytic research involving both K-12 and college students yielded no statistically significant differences between online and in-person learners on measures of achievement, attitudes toward learning, and retention (Bernard et al., 2004). Some studies have suggested that students acquire more knowledge (e.g., Gross et al., 2022) and perform better when learning in-person (e.g., Xu & Jaggars, 2011), while other studies indicate that online formats confer greater performance benefits (e.g., Dutton et al., 2001; Schneider et al., 2022), particularly when students have a history of high academic achievement (e.g., Calafiore & Damianov, 2011; Cavanaugh & Jacquemin, 2015). Adding to this pattern of mixed findings, research involving a summer science enrichment program has shown no format-dependent differences in facilitating students' scientific competence development, although students reported preferring an in-person over an online format for the interpersonal engagement the former affords (Carey et al., 2022). Although the relationship between instructional format and academic performance remains unclear, the relationship between format and persistence is less ambiguous. Research suggests that students in online courses tend to drop out prematurely (e.g., Dutton et al., 2001; Hart et al., 2018), which raises the question as to whether they may have difficulty sustaining motivation. The isolative nature of online learning may disrupt students' ability to maintain interpersonal contact and build a sense of community with others (Morris et al., 2021; Race et al., 2021), ultimately thwarting satisfaction of the fundamental drive for social belonging (Baumeister & Leary, 1995).

Self-Determination Theory

Understanding the motivational processes associated with learning both prior to and during the pandemic may provide some insight into how pedagogical strategies can be adapted in a way that optimizes student learning and achievement regardless of the mode of delivery. Self-determination theory (SDT; Ryan & Deci, 2000) represents a useful framework from which to understand these processes. SDT proposes that people strive to satisfy three basic psychological needs – autonomy, competence, and relatedness – in an effort to realize inborn tendencies toward optimal growth and functioning. Satisfaction of these needs occurs to the extent that conditions in the environment are perceived to be autonomy-supportive versus controlling, manifesting in motivation that is commensurate in quality with these environmental features. Contexts that satisfy these needs tend to facilitate intrinsic motivation whereas contexts that thwart these needs are theorized to result in less adaptive forms of regulation such as extrinsic motivation and amotivation (see Ryan & Deci, 2000, for a review).

The majority of research on student motivation in science education settings has focused on the degree to which students' needs for autonomy are supported. Longitudinal research suggests that autonomy-supportive teaching promotes later autonomous motivation among science students (Jungert & Koestner, 2015), and Hagger and colleagues (2015) similarly obtained longitudinal evidence of positive indirect effects of teachers' autonomy support on students' out-of-school math homework behavior. Very few studies have focused explicitly on relatedness-supportive teaching, however, Wood (2019) argued that strong social bonds between teachers and students offer an important foundation for the satisfaction of the basic psychological needs. Some studies have shown that online learning environments promote need satisfaction (e.g., Hsu et al., 2019) while others have linked online learning to significantly lower perceptions of competence and relatedness as well as a diminished sense of interpersonal warmth (Chiu, 2021).

Summer Science Program

The Summer Science Program (SSP) is a 39-day residential program in which high-ability high school students engage in authentic astrophysics and biochemistry research. The program is designed to create a community of practice in which students and faculty work together on a central research project by sharing ideas, research methods, and discoveries in a supportive environment. The astrophysics program uses a combination of classroom instruction, hands-on observing time at a telescope, and problem sets to teach participants the mathematical and astronomical techniques required to determine the orbit of an asteroid based on observations of its position. In the online program participants used asteroid observations gathered from remote telescopes, relaying instructions to telescope operators and receiving the requested images which were then used for analysis. Classroom instruction was replaced with synchronous and asynchronous (recorded) lectures, online office hours and review sessions with faculty, and drop-in sessions set aside for homework collaboration or freeform socialization/discussion, monitored by faculty.

In the biochemistry program participants begin with an uncharacterized gene sequence and knowledge that the gene is required for crop infection by fungal pathogens. Using bioinformatic tools they develop an hypothesis about the identity of the protein encoded by this gene, then use classical wet lab biochemical methods such as protein purification and enzyme activity, specificity, and inhibition measurements to evaluate their hypotheses and test if their enzyme is similar enough to the well-characterized ortholog from a research model organism to justify use of the ortholog's atomic structure for inhibitor design. They then use computational tools to create a structural model of their enzyme and rationally design specific inhibitors that could form the basis for a novel crop-protecting fungicide. Lab work is supported by parallel classroom instruction on fundamentals of enzyme structure and function, and the biochemical methods being used in the lab. Assignments focus primarily on learning analytical and computational methods, literature searching for hypothesis development, and experimental design. In the online version, participants were provided with previously collected data to analyze and watched videos demonstrating how the experiments were performed. The bioinformatics and computational modeling components were expanded, and a Python coding module was implemented to teach participants how to create an algorithm for predicting biological substrates and functions for their enzymes in their respective pathogen species. In both programs, participants work in teams of three to perform the research, including formulating hypotheses, collecting and analyzing data, and disseminating results.

Current Study

Student science motivation has been studied extensively in traditional learning settings, but there is a dearth of research examining how such motivation may be impacted in online vs. in-person learning environments. Prior research has established the utility of psychological needs as temporal antecedents of intrinsic motivation for authentic research in a traditional in-person learning environment (Deemer et al., 2022), but little is known about how these needs themselves are nurtured over time in both traditional and online learning settings. The purpose of the current study was twofold. Our primary aim was to determine the extent to which these learning environments differentially predict growth in students' needs for autonomy, competence, and relatedness. Secondarily, we were interested in understanding whether students perceive the SSP specifically as representing the source of their need satisfaction. We predicted that students' perceptions of autonomy (hypothesis 1), competence (hypothesis 2), and relatedness (hypothesis 3) would grow significantly over the course of the program. We also hypothesized that the online SSP format would be associated with a faster rate of growth in autonomy compared to the in-person version. Despite this, we reasoned that the online version would likely not optimize skill development because online instructors are not physically present to guide students in the hands-on use of equipment, materials, and techniques. We therefore hypothesized that the in-person format would be associated with a faster rate of competence need satisfaction than the online format. Finally, we reasoned that the inability of participants to physically interact with others in the online format would limit their ability to form strong social bonds. On this basis we hypothesized that the in-person format would be associated with a faster rate of growth in relatedness than the online format.

Method

Participants

A total of 598 SSP participants (268 in-person, 330 online) took part in the study. The sample was balanced with respect to gender as 290 of the participants identified as male, 289 identified as female, and 3 participants reported a nonbinary gender identity. Sixteen participants did not report their gender. Age ranged from 15 to 18 with a mean of 16.65 ($SD = 0.59$). Most participants identified as East Asian (197), followed by White/European American (114), Indian (83), multiracial (42), Hispanic/Latino/Latina (35), Black/African American (20), Southeast Asian (18), Arabic/Middle Eastern (8), and Pacific Islander (2). Seven participants identified as "other", 34 indicated they preferred not to disclose their race/ethnicity, and 38 did not provide a response to the race/ethnicity item. Most participants were residents of suburban (67.6%) communities (24.9% urban, 7.5% rural) and were largely enrolled in public high schools (60.8%), followed by private (25.4%), magnet (5.9%), charter (2.8%) and all other high school types (e.g., home school).

Measures

Psychological Need Satisfaction The Basic Need Satisfaction at Work Scale (Deci et al., 2001) was used to measure participants' perceptions of the degree to which the program satisfied their basic psychological needs. This measure consists of 21 items that span three subscales: autonomy (7 items), competence (6 items), and relatedness (8 items). The items were originally developed to measure need satisfaction at work but in the current study these items were adapted by substituting terms referencing work with terms that refer to SSP. For example, an original relatedness item states "I get along with people *at work*." The adapted version of this item states "I get along with people *in this program*." Items are rated on a Likert scale ranging from 1 (*not at all true*) to 7 (*very true*).

Procedure

The study was approved by the first author's institutional review board prior starting data collection. Informed written consent was obtained from the parents of all participants under the age of 18 and from the participants themselves if they were 18 years old. Participants under the age of 18 also provided their written assent to engage in the study. SSP has historically been administered as an in-person learning experience, but the program was converted to a fully online format in June 2020 following the onset of the COVID-19 pandemic. The data were collected from 2018 to 2021, with pre-pandemic participants (2018–2019) comprising the in-person learning group and pandemic participants (2020–2021) comprising the online group.

Within-program data were collected across four measurement occasions using an online survey. Information on participants' demographic backgrounds was collected one week prior to the start of the program at time 0 (T0). Data on the substantive variables were collected at 11-day intervals following the start of the program.

Data Analytic Strategy

We tested the hypotheses by estimating separate latent growth curve models for the autonomy, competence, and relatedness variables. A graphical depiction of the general model is presented in Fig. 1. Total scores for the need satisfaction variables at T1, T2, and T3 represent indicators of the latent intercept and slope growth factors. We first estimated baseline growth models to assess the trajectories of the need satisfaction variables. After establishing optimal baseline models we added the time-invarying predictors of format type (0 = online, 1 = in-person) and project type (0 = astrophysics, 1 = biochemistry) to determine whether the intercept and growth factors were conditioned upon these variables. Finally, we computed format x project interaction terms and estimated these variables as predictors of the growth trajectories to evaluate whether the effect of online vs. in-person instruction on motivation was contingent upon the type of project that students were involved in. The analyses were performed using Mplus 7.4 statistical software (Muthén & Muthén, 1998–2015). Maximum likelihood was used as the estimation method and model fit was evaluated using the following indexes: (a) comparative fit index (CFI); (b) model chi-square test; (c) root mean square error of approximation (RMSEA); (d) standardized root mean square residual (SRMR); and (e) Tucker-Lewis index (TLI).

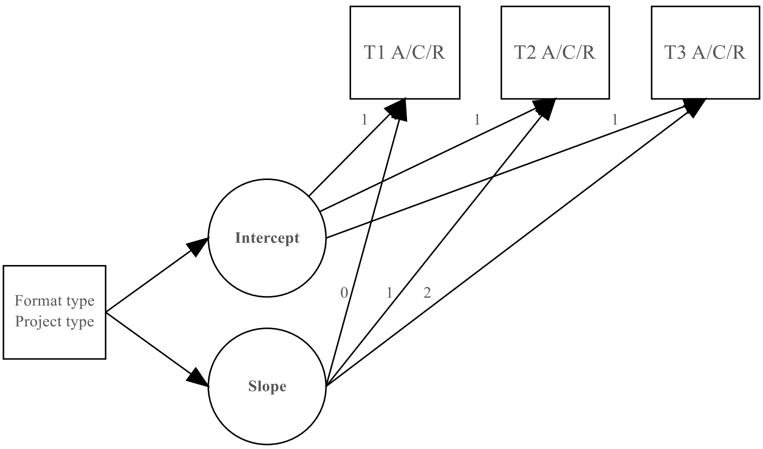

Fig. 1 General model of conditional latent growth in needs for autonomy, competence, and relatedness. *Note.* A = autonomy, C = competence, R = relatedness

Results

Zero-order correlations and descriptive statistics are presented in Table 1. The need satisfaction variables were all significantly and positively correlated across all measurement occasions. Estimation of the baseline autonomy growth model revealed a very good fit to the data, $\chi^2 = 7.39$, $p = 0.06$, CFI = 0.993, RMSEA = 0.055 (90% CI: 0.000, 0.107), TLI = 0.993, SRMR = 0.055. The mean intercept and slope were 33.68 ($p < 0.001$) and 0.87 ($p < 0.001$), respectively, indicating that participants reported rather high initial levels of autonomy which increased significantly over time. Our first hypothesis was therefore supported. The baseline model for competence growth also offered an acceptable fit to the data, $\chi^2 = 9.26$, $p = 0.03$, CFI = 0.990, RMSEA = 0.066 (90% CI: 0.020, 0.116), TLI = 0.990, SRMR = 0.010. The mean intercept (estimate = 31.04, $p < 0.001$) and slope (estimate = 0.98, $p < 0.001$) growth factors were both significant, thus supporting our second hypothesis. Finally, the fit of the relatedness model to the data was good, $\chi^2 = 6.00$, $p = 0.11$, CFI = 0.996, RMSEA = 0.046 (90% CI: 0.000, 0.099), TLI = 0.996, SRMR = 0.070. Both the mean intercept (estimate = 47.74, $p < 0.001$) and slope (estimate = 0.81, $p < 0.001$) growth factors were significant, thus supporting hypothesis 3.

Having demonstrated evidence of unconditional growth in the need satisfaction variables, we next added the format and project type predictors to the models. Results for each outcome are presented in Table 2. The conditional autonomy model provided a very good fit to the data, χ^2 (5) = 10.88, $p = 0.05$, CFI = 0.991, RMSEA = 0.050 (90% CI: 0.000, 0.091), TLI = 0.984, SRMR = 0.035. Format type was a significant negative predictor of the intercept growth factor (B =—2.31, $p < 0.001$), indicating that participants in the in-person learning group reported lower initial perceptions of autonomy than participants in the online learning group. Contrary to prediction, however, format type was not significantly associated with the slope factor (B =—0.33, $p = 0.127$). Thus, the hypothesis that online learning would be associated with increased autonomy relative to in-person learning was not supported. The fit of the competence model to the data was also quite good, χ^2 (5) = 17.23, $p < 0.01$, CFI = 0.981, RMSEA = 0.072 (90% CI: 0.037, 0.111), TLI = 0.965, SRMR = 0.068. Format type was a significant negative predictor of the intercept factor (B =—0.99, $p = 0.029$) but it was not associated with the slope factor (B =—0.11, $p = 0.556$), therefore the hypothesis that in-person learning would be associated with increased competence relative to online learning was not supported. The relatedness growth model offered an excellent fit to the data, χ^2 (5) = 7.29, $p = 0.20$, CFI = 0.997, RMSEA = 0.031 (90% CI: 0.000, 0.076), TLI = 0.994, SRMR = 0.043. Despite the model fit, format was not predictive of either the relatedness intercept factor (B =—0.11, $p = 0.838$) or the relatedness growth factor (B =—0.20, $p = 0.342$). The hypothesis that in-person learning would be positively associated with relatedness growth was therefore not supported.

To examine whether the relationship between format type and growth in need satisfaction was conditional upon project type, we computed the format x project interaction term and entered this variable as an additional predictor in the models. The fit of the autonomy model to the data was excellent, χ^2 (6) = 10.13, $p = 0.12$, CFI = 0.994, RMSEA = 0.038 (90% CI: 0.000, 0.078), TLI = 0.988, SRMR = 0.030, as the interaction term was a significant predictor of both the intercept (B =—2.87, $p = 0.004$) and growth ($B = 1.11$, $p = 0.012$) factors. A plot of the 95% confidence bands for the conditional effect of format on autonomy growth is presented in Fig. 2. A 1-unit increase in format type from 0 (online learning) to 1 (in-person learning) was associated with a roughly -0.7 unit decrease in the rate

Table 1 Zero-order correlations and descriptive statistics for the demographic and need satisfaction variables

Variable	1	2	3	4	5	6	7	8	9	10	11	12
1. Gender	–											
2. Format	.02	–										
3. Project	.01	-.05	–									
4. T1 autonomy	-.03	-.20***	-.12*	–								
5. T2 autonomy	-.03	-.24***	-.06	.71***	–							
6. T3 autonomy	-.03	-.25***	-.11*	.71***	.77***	–						
7. T1 competence	-.10*	-.06	.05	.52***	.42***	.38***	–					
8. T2 competence	-.10	-.18***	.01	.45***	.57***	.47***	.72***	–				
9. T3 competence	-.11*	-.10*	.04	.41***	.48***	.51***	.68***	.76***	–			
10. T1 relatedness	.00	.02	-.10	.49***	.38***	.37***	.44***	.37***	.36***	–		
11. T2 relatedness	-.05	-.04	-.05	.34***	.45***	.36***	.35***	.47***	.41***	.75***	–	
12. T3 relatedness	-.03	-.05	-.05	.37***	.35***	.47***	.37***	.38***	.46***	.74***	.77***	–
13. *M*	.50	.51	.45	33.51	34.62	35.33	31.09	31.85	33.10	47.75	48.73	49.47
14. *SD*	.51	.50	.50	5.41	5.14	5.48	4.80	4.91	4.74	5.76	5.20	5.55
15. α	–	–	–	.67	.67	.67	.64	.70	.66	.82	.80	.83

$^{*}p < .05$. $^{***}p < .001$

Table 2 Results of conditional latent growth curve analysis of autonomy, competence, and relatedness

	Intercept Growth Factor			Slope Growth Factor		
Outcome/Predictor	*B*	*SE*	β	*B*	*SE*	β
Autonomy						
Format	-2.31***	.49	-.25	-.33	.22	-.16
Project	-.52	.50	-.06	-.19	.22	-.09
Competence						
Format	-.99*	.45	-.12	-.11	.19	-.08
Project	.45	.46	.05	.02	.20	.01
Relatedness						
Format	-.11	.54	-.01	-.20	.21	-.11
Project	-.94	.54	-.09	.32	.21	.18

*$p < .05$. ***$p < .001$

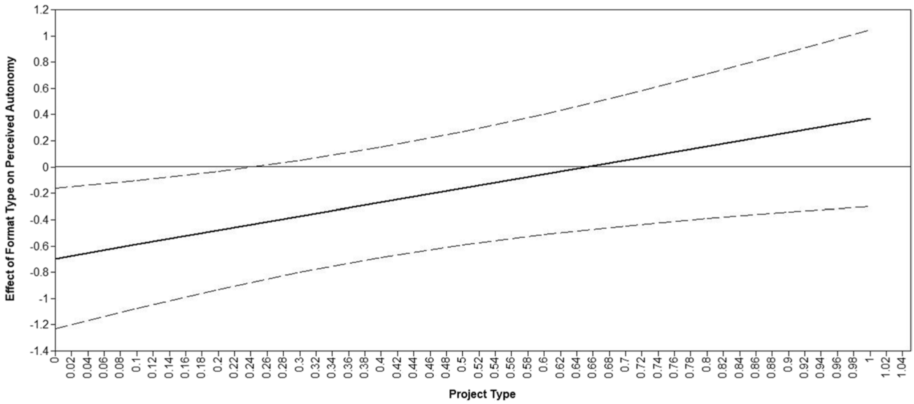

Fig. 2 Plot of 95% confidence bands for the interactive effect of format and project type on autonomy need satisfaction growth. *Note*. Format type is coded 0 = online, 1 = in-person; project type is coded 0 = astrophysics, 1 = biochemistry

of autonomy growth per measurement occasion for the astrophysics students and a 0.4 unit increase for the biochemistry students. Because zero was contained in the confidence interval for the astrophysics group only, the simple slope was significant for this group but not the biochemistry group. Plots of the autonomy means for each project group further illustrate the nature of the interaction (see Fig. 3). Astrophysics students' perceptions of autonomy in the online condition grew more substantially than those of students in the in-person condition whereas the autonomy trajectories for the biochemistry students were more similar across instructional format.

The competence model provided a good fit to the data, χ^2 (6) = 17.21, $p = 0.09$, CFI = 0.982, RMSEA = 0.063 (90% CI: 0.029, 0.099), TLI = 0.964, SRMR = 0.060. The interaction term was not predictive of the intercept factor (B =—1.59, $p = 0.084$) but it was a significant predictor of the slope factor ($B = 0.901$, $p = 0.024$). As Fig. 4 indicates, a 1-unit increase in format type from online learning to in-person learning was associated with a -0.45 unit decrease in the rate of competence growth per measurement

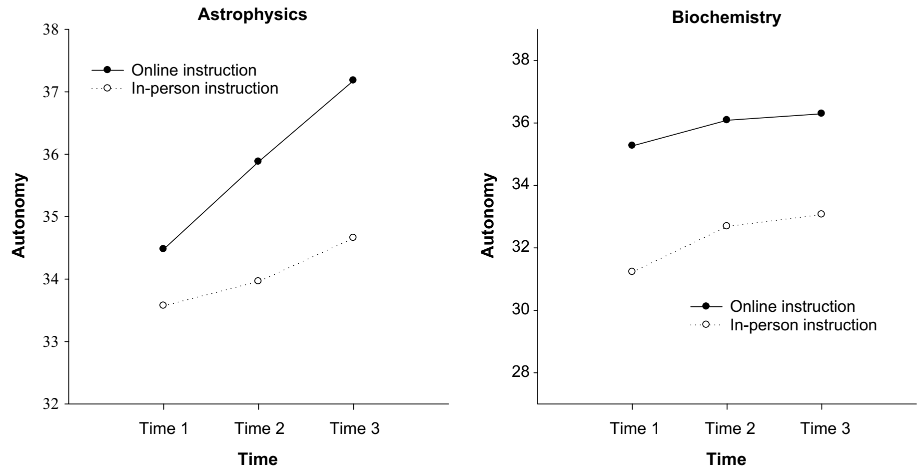

Fig. 3 Autonomy sample means for the astrophysics and biochemistry groups receiving online and in-person instruction

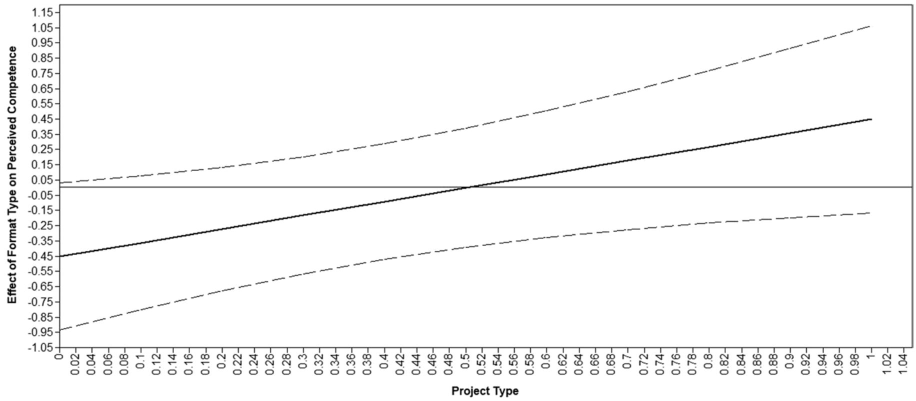

Fig. 4 Plot of 95% confidence bands for the interactive effect of format and project type on competence need satisfaction growth. *Note*. Format type is coded 0 = online, 1 = in-person; project type is coded 0 = astrophysics, 1 = biochemistry

occasion for the astrophysics students and a 0.45 unit increase for the biochemistry students. Zero was contained in the confidence intervals for both project groups therefore their simple slopes were not significant. We plotted the group means across conditions to further examine the nature of the interaction (see Fig. 5). Astrophysics students' competence perceptions began at approximately the same point but the online students' competence grew more precipitously than those in the in-person condition. Conversely, online biochemistry students' competence perceptions began at a higher level but grew at a slower rate than those of their in-person counterparts. Estimation of the relatedness model yielded an excellent fit to the data, χ^2 (6) = 9.65, p = 0.14, CFI = 0.995, RMSEA = 0.036 (90% CI: 0.000, 0.076), TLI = 0.989, SRMR = 0.036, however, the

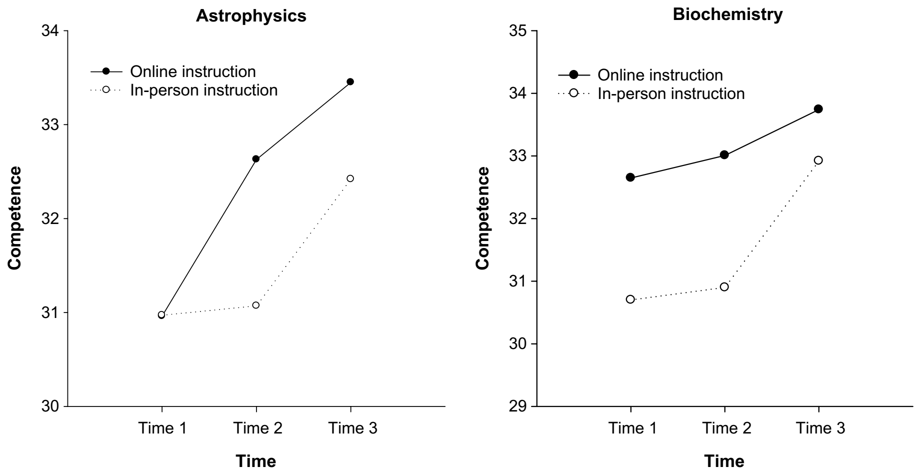

Fig. 5 Competence sample means for the astrophysics and biochemistry groups receiving online and in-person instruction

interaction term was predictive of neither the intercept (B = -1.01, p = 0.354) nor the slope (B = 0.671, p = 0.118) factor.

Discussion

Our chief objective in conducting this research was to examine differential growth patterns of psychological need satisfaction among adolescents receiving online and in-person instruction in an informal science enrichment program. Growth in autonomy, competence, and relatedness occurred regardless of instructional format, thus supporting our first three hypotheses. Our results indicate that SSP participants increasingly perceived the program as affording them the ability to make their own choices with respect to how they performed tasks and met learning objectives, express their ideas candidly and without coercion, develop their competence as budding scientists, and form satisfying relationships with peers and instructors. Participants endorsed perceptions of relatedness to a greater extent than autonomy and competence considering the mean scores for relatedness at all three time points most closely approached the upper end of the range of observed scores. The high levels of perceived relatedness suggests that participants viewed SSP as an interpersonally engaging milieu in which to develop their scientific skills.

We hypothesized that there would be main effects of format type in predicting growth in the psychological needs but these predictions did not come to fruition. That is, the online format was not in itself significantly associated with autonomy growth and the in-person format was not associated with growth in either competence or relatedness need satisfaction. Our findings parallel those of Carey et al. (2022) in suggesting there is no clear consensus as to the preferred instructional format for optimizing science learning outcomes. Rather, the current results indicate that the effect of format type on science motivation development is contingent upon the type of learning tasks students are engaged in. Our findings are consistent with prior research documenting the efficacy of SSP in promoting students' perceptions of autonomy (Deemer et al., 2022), however, we were surprised to observe that this effect was enhanced in the online implementation as students participating in the online astrophysics project reported significantly greater growth in their autonomous motivation than astrophysics students in the in-person condition. The astrophysics project is ideally suited for an online format because many of its activities can be performed remotely. For example, asteroid orbit data are gathered remotely from telescopes in both in-person and online versions of SSP, and can be analyzed using software that all participants have online access to. When considering these practical features in conjunction with the autonomy-supportive philosophy of teaching that is characteristic of SSP, then it becomes clearer as to why the online astrophysics project was associated with such robust autonomous learning. In contrast, the biochemistry project is not easily adapted for an online platform because here participants typically engage in intense hands-on experimentation in an actual laboratory. The reduced growth in autonomy in the online biochemistry project may thus reflect the absence of the opportunity to successfully master a critical aspect of this project in an online format.

We observed a similar format x project interaction in predicting competence growth whereby in-person astrophysics participants perceived a declining rate of growth in this outcome compared to online participants, and in-person biochemistry students perceived an increasing rate of growth compared to online biochemistry participants. This finding regarding astrophysics participants is perhaps more surprising than the autonomy finding because one might reasonably expect that competence perceptions would develop more rapidly in a traditional learning environment where astrophysics instructors are physically present to answer questions and assist students with any problems they may experience in interpreting data. A plot of the competence means within the astrophysics condition revealed that the online and in-person participants essentially started at the same point but online participants' perceptions of competence grew more rapidly than those of the in-person participants. Online biochemistry students' competence perceptions started at a reasonably high level and did not grow much beyond that point while in-person biochemistry students started at a markedly lower level but reached a point approaching that of the online participants by the end of the program. Perhaps the in-person biochemistry participants perceived the hands-on aspect of their project to be quite challenging early in the program but once they developed some proficiency with the project's tasks and began seeing the results of their experiments, they perceived a substantial increase in their skill development between the second and third measurement occasions. Hands-on learning skills take time to develop, therefore students who are striving to master these skills may experience some self-doubt and perhaps see themselves as less capable relative to students who are not experiencing that aspect of learning. Between-format differences in the competence growth trajectories may thus be attributable to differences in perceptions of task difficulty as a result of qualitative differences in assigned tasks and students' appraisals of their abilities; it would be important to measure these perceptions in future research on the SSP.

The fact that we did not observe hypothesized between-format differences in the growth rates of relatedness was also surprising. It appears that being within physical proximity of others did little to increase in-person participants' perceptions of social connectedness relative to the online participants. The online participants had ample opportunity to communicate, whether it was in large group sessions or breakout sessions involving small groups, and it appears that the quality and frequency of this dialog nullified any advantage that face-to-face communication in the in-person condition might have offered. We should also note that social connections developed outside of formal learning situations were not examined. The in-person version of SSP has traditionally been a residential program in which participants have engaged in more than just academic activities. Capturing the influence of these settings on relatedness perceptions would represent an important avenue for further research.

There are two key limitations in this study that may influence how the results are interpreted. First, we did not include in the study the various forms of self-regulation that are posited by SDT to operate as a function of psychological need satisfaction. Although we found that the online format was associated with a greater rate of autonomy growth than the in-person format for astrophysics students, it remains to be seen whether participants viewed the online version of SSP as offering interesting and enjoyable content, personally important content that was instrumental to the development of their scientific skills, or content that was necessary to learn because their parents and other authority figures believed it was important. Finally, our findings apply only to students involved in informal science enrichment programs, which limits the extent to which the findings generalize to students in formal science settings. Examining relations between instructional format and student motivation development in science classrooms would be an important next step in this area of research.

Conclusions

In sum, the COVID-19 pandemic has forced many science educators to move their courses online but until recently very little was known about the efficacy of teaching in this format compared to traditional teaching methods. The current study contributes to this body of evidence but rather than focusing on learning outcomes, we examined the differential impact of these science teaching methods on student motivation. Online instruction was found to be just as effective as a traditional face-to-face format in facilitating student motivation provided the learning tasks can be performed autonomously in a digital environment. This illustrates the importance of determining when certain educational content may best be offered online and when it would be better offered in-person. Pre-pandemic advancements in digital technologies prepared the education landscape for a shift toward more hybrid-based instruction, and the field of education had been moving in this direction for years, but the pandemic has arguably cemented this move toward hybrid pedagogies as a permanent one. Indeed, it is important to consider the possibility that the increased frequency of online science learning in recent years has facilitated the ability of learners to adapt quickly to the demands of changing learning tasks and technologies that deliver increasingly authentic online instructional material. Such changes in students' online navigational and learning habits offer valuable opportunities for further application of instructional content to online platforms by SSP and other science education programs. Understanding when and why science instructors should alter their instructional platform will thus be critical moving forward. It is hoped that the current research helps elucidate the conditions that drive these decisions.

Data Availability The data and analysis code for this study are available by emailing the first author.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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