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Gene—environment interaction between gaming addiction and perceived stress in late adolescents and young adults: A twin study

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FULL-LENGTH REPORT

ABSTRACT

Background and aims: The association between perceived stress (PS) and gaming addiction (GA) is well documented. However, the mechanism for explaining this association remains unclear. Using a genetically informative design, this study aims to distinguish between the diathesis-stress and bio-ecological models of gene by environment interaction (G x E) to explain the underlying mechanism of the relationship. *Methods:* In total, 1,468 twins (mean age = 22.6 ± 2.8 years) completed an online survey including the GA and PS scales. Twin correlations for GA and PS were computed and univariate model-fitting analysis was conducted to determine genetic and environmental influences on GA and PS. The bivariate G x E model-fitting analysis was performed to determine the best G x E interaction model. *Results:* Additive genetic, shared environmental, and non-shared environmental effects were 0.70 (95%CI = 0.61, 0.77), 0.00, and 0.30 (95%CI = 0.26, 0.33), and 0.38 (95%CI = 0.24, 0.55), 0.35 (95% CI = 0.18, 0.51), and 0.22 (95%CI = 0.20, 0.26) for GA and PS, respectively. Bivariate G x E model-fitting analysis supported the diathesis-stress model, where genetic influences on GA were greater in higher levels of PS, whereas environmental influences on GA were small and constant across levels of PS. *Discussion and conclusions:* The evidence for the diathesis-stress model for GA is consistent with the etiological process of many forms of psychopathology. The findings should be incorporated in clinical settings to improve the treatment of GA, and used in developments of intervention and prevention methods for GA.

KEYWORDS

gaming addiction, perceived stress, diathesis-stress model, twins, genetic vulnerability

INTRODUCTION

Over the past years, game use has substantially increased worldwide, with emerging concerns that gaming addiction (GA) is associated with poor health (Lam et al., 2010; Yen, Yen, Chen, Tang, & Ko, 2009). Moreover, the excessive use of games may lead to impaired daily life activities such as sleep deprivation, failure to exercise, and academic under-achievement (El et al., 2019). Internet gaming disorder (IGD) has been included in Appendix of Diagnostic and Statistical Manual of Mental Disorders 5 (DSM-5; American Psychiatric Association, 2013) as a condition that requires further study. A recent review of published studies of IGD concluded that the international prevalence in general populations ranged from 0.2% to 57.5% (Darvesh et al., 2020). The wide range of the prevalence found in the review was due to the diversity of diagnostic criteria and questionnaires used in studies. The present study defined GA as preoccupation with games, tolerance, withdrawal, failure to reduce or stop gaming, continued gaming despite problems, and relationship risk due to excessive gaming. This definition followed the description of IGD in the DSM-5 and the gaming disorder in the International Classification of Diseases. However, note that in the literature of gaming and internet related disorders, the term, GA has been used interchangeably with IGD,

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pathological video gaming, internet addiction, problematic internet use, compulsive internet use, etc. (King, Haagsma, Delfabbro, Gradisar, & Griffiths, 2013).

It is now well documented that high levels of stress are associated with increased severity of GA, indicating that stress is a major risk factor for the development of GA (Ropovik et al., 2023; Sung, Nam, & Hwang, 2020). Although the association between GA and stress is established, only a few studies have proposed the potential mechanisms that underlie this association. For example, the general strain theory proposes that various types of stress cause negative emotions, which, in turn, lead to deviant behaviors such as internet addiction (Agnew, 1992; Jun & Choi, 2015). Similarly, the theory of compensatory internet use suggests escapism for explaining the association between stress and GA (Kardefelt-Winther, 2014). To avoid negative affective states and ease feelings of distress associated with stressors, individuals may escape into games and immerse themselves in playing games. According to these theories, GA can be considered a behavioral response to stressful life events.

Although underlying mechanisms of the observed associations between stress and GA remain uncertain, twin studies showed that GA and internet related disorders were heritable. Monozygotic (MZ) twins share 100% of their genes, whereas dizygotic (DZ) twins share, on average, 50% of their genes. Utilizing this difference in the proportion of genes shared between MZ and DZ twins, one can estimate genetic and environmental influences on variables. Using Chinese adolescent twins, Li, Chen, Li, and Li (2014) found that genetic influences on problematic internet use were 58%–66%. Vink, van Beijsterveldt, Huppertz, Bartels, and Boomsma (2015) also showed that heritability of compulsive internet use was 48% in Dutch adolescent twins. Sex differences in genetic influences were inconsistent: Li et al. (2014) found higher levels of heritability in boys than in girls, whereas Vink et al. (2015) found no significant sex differences. In line with substantial genetic influences found in these twin studies, the first genome-wide association studies identified 72 single nucleotide polymorphisms in 24 genes associated with internet addiction disorder (Haghighatfard et al., 2023).

Given the evidence of genetic influences on GA, the present study intended to examine the underlying process of the relationship between stress and GA using the framework of the gene by environment interaction (G x E) effects (Plomin, DeFries, & Loehlin, 1977). G x E effects refer to genetic sensitivity to environmental effects on phenotype, such that the impact of the environment may vary depending on genetic vulnerability of individuals and vice versa (Plomin et al., 1977). G x E effects are thought to constitute a key mechanism through which genes influence human behavior and psychopathology (Moffit, Caspi, & Rutter, 2006). In the context of G x E, the environment may serve to activate or attenuate genetic vulnerability to GA. G x E effects can take many forms (Belsky & Pluess, 2009). The present study considered two types of G x E effects, namely, the diathesis-stress model (Ingram & Luxton, 2005) and the bio-ecological model (Bronfenbrenner & Ceci, 1994). The diathesis-stress model emphasizes the role of stress in the activation of genetic vulnerability, such that those with greater genetic predisposition will exhibit high levels of GA in more stressful environments. In this model, genetic influences on individual differences in GA are expected to be large in risky environments and small in neutral or positive environments (absence of stress). The reason is that adverse environments (stress) can precipitate the expression of genetic factors in GA. Environmental influences on GA are expected to be small or attenuated across levels of stress. As an example, using 17-year-old twins, Hicks, South, Dirago, Iacono, and McGue (2009) examined G X E effects to determine the mechanisms linking environmental stresses (parental discord, poverty, family legal and mental health problems) to substance use. The authors demonstrated that genetic influences on substance use were much larger in higher than lower levels of stresses, while environmental influences were relatively stable and modest across levels of stresses, which was consistent with the expectation from the diathesis-stress model.

By contrast, the bio-ecological model focuses on contextual factors, including families, schools, and neighborhood and assumes that adverse environments can directly shape the development of GA. Thus, environmental influences are expected to be strong in risky environments, whereas genetic influences are suppressed. At low or medium levels of environmental risk, genetic influences are expected to be strong. As an illustrative example, Dash et al. (2023) studied G X E effects on the relationship between externalizing behaviors and stressful experiences (e.g., death of a family member, witnessing a crime) in 11–12 year old twins. The authors found that genetic influences on externalizing behaviors decreased and environmental influences on externalizing behaviors increased with increase in stress, supporting the bio-ecological model.

As twin studies use a genetically informative design, it provides a powerful method for distinguishing between the diathesis-stress and bioecological models to explain the underlying process of the relationship between GA and stress. Using a sample of adolescent and young adult twins, the present study aimed to (1) estimate genetic and environmental influences on GA and perceived stress (PS), and (2) explore the pattern of G X E effects on the relationship between PS and GA. To date, no twin studies examining G X E effects on the relationship between GA and PS have been published. As findings for G X E effects on substance use and related disorders were mixed in the literature, specific hypotheses were not formed in the present study. If perceived PS moderates genetic influences on GA, such that genetic influences on GA are high in high levels of PS, then the diathesis-stress model would be supported. In contrast, if PS moderates environmental influences on GA, such that environmental influences are high in high levels of PS, then, the bio-ecological model would be supported.

MATERIALS AND METHODS

Sample

The participants comprised of 1,547 twins who responded to an online survey regarding GA and related traits conducted by the Korea Twin Research Institute (KTRI) in 2022–2023. The survey was developed for late adolescents and young adults because this age group was considered vulnerable to GA. The survey link was uploaded on online communities in various universities and in the nation as well as the websites of the KTRI and twin clubs in South Korea. Of 1,547, 79 individuals were excluded from data analysis, because their zygosity was ambiguous ($N = 16$) or their ages were 30 years or older ($N = 26$) or under 15 years old ($N = 37$). The final sample (total $N = 1{,}468$, 734 complete pairs) consisted of 435 MZ and 299 DZ twin pairs that included 130 pairs of opposite-sex DZ twins. Females outnumbered males (64% vs. 36%) in the sample partly because military service is mandatory for South Korean young adult men. Moreover, females tend to respond to online surveys more frequently than males do (Wu, Zhao, & Fils-Aime, 2022). Although we attempted to recruit late adolescents and young adults, 77% of the participants were young adults. The mean (SD) age of the total sample was 22.63 (±2.83) years.

The zygosity of twins was determined using four questions on the physical similarity of twins, the frequency of confusion about twins by others, and the self-perception of zygosity adopted from a zygosity questionnaire developed by Ooki, Yamada, and Asaka (1993). The higher numbers of MZ than DZ twins (59% vs. 41%) in the present sample likely reflected the twin birth rates in South Korea in which spontaneous DZ twin birth rates are lower than those of MZ in the 1990s and early 2000s (Hur, 2021).

Measures

Gaming addiction. GA was assessed with 20 items from the Korean Game Addiction scale developed by Choi, Ryong, and Kim (2013). The 20 items measure tolerance, withdrawal, compulsive use of games, impairment of self-control, impairment of daily activities, excessive time consumption for gaming, and continued gaming despite problems over the past one year. An example item includes: "I tried to reduce or stop playing games several times but failed". Items were rated on a 0 ("not at all true") to 3 ("almost always true") scale and summed to create a total score, which ranged from 0 to 60 with higher scores indicating greater symptom severity. The scale showed good psychometric properties (Choi et al., 2013). In the present sample, the Cronbach alpha reliability of 20 items was 0.96.

Perceived stress. PS was measured with 20 items adopted from the Life Stress Scale developed for late adolescents and college students (Chon, 1998). The 20 items assess subjective perception of daily stress in five domains (i.e., academic, family financial difficulties, family conflicts, friendship, and future career) over the past six months. An example item is: "there was conflict with parents due to their excessive interference". Items were rated on a 0 ("not at all true") to 4 ("very true") scale and summed to create a total score, which ranged from 0 to 80 with higher scores indicating greater perception of stress. The scale demonstrated good psychometric properties (Chon, 1998). In the present sample, the Cronbach alpha reliability of the 20 items was 0.92.

Statistical analysis

Data analysis consisted of descriptive statistics, twin correlations, univariate model-fitting, and bivariate G x E model-fitting analyses. To estimate genetic influences on GA and PS, MZ and DZ twin correlations were computed and univariate model-fitting analyses were conducted. To choose between the diathesis-stress and bio-ecological models, bivariate G x E model-fitting analyses were performed.

The total variances and covariances of GA and PS were decomposed into additive genetic (A), shared environment (C), and non-shared environmental variance plus measurement error (E) components. "A" represents the average effect of all alleles influencing a variable; "C" denotes shared environmental factors shared between the two members of a twin pair that make them similar, and "E" refers to those environmental factors unique to each member of a twin pair that make them different. Significant "A" is implicated when MZ twin correlation is greater than DZ twin correlation, whereas significant "C" is suggested when DZ twin correlation is greater than half of the MZ twin correlation. "E" is suggested when MZ twin-correlation is less than one. Because twins are the same age and gender, failing to adjust for the effects of age and sex when they exist will result in biased estimation of twin correlation and parameters in model-fitting analysis (McGue & Bouchard, 1984). Thus, prior to twin correlation and model-fitting analyses, data were combined across males and females and corrected for sex, age, age^2, and age X sex effects using multiple regression analysis (McGue & Bouchard, 1984). The standardized residuals were used in data analysis.

Figure 1 presents the bivariate G x E model (Purcell, 2002; van der Sluis, Posthuma, & Dolan, 2012), where PS interacts with "A", "C", and "E" effects common to PS and GA (A_c, C_c, and E_c, respectively), and those effects unique to GA (A_u, C_u, & E_u, respectively). The interaction effects of moderator (M: PS in this study) are added to "A", "C", and "E" effects common to PS and GA ($a_c + \beta_{ac}M$, $c_c + \beta_{cc}M$, $e_c + \beta_{ec}M$) and those unique to GA ($a_u + \beta_{au}M$, $c_u + \beta_{cu}M$, $e_u + \beta_{eu}M$). The regression weights (β terms) are unknown parameters estimated from the data that represent the extent to which PS (M) moderates the magnitudes of common and unique "A", "C", and "E" effects on GA. An interaction effect is evidenced if the β terms are significantly different from zero.

Mx (Neale, Boker, & Xie, 2003) was used to compute maximum likelihood MZ and DZ twin correlations and to conduct model-fitting analyses. The maximum likelihood raw data option in Mx calculates twice the negative log-likelihood (−2LL) of the data. The difference in −2LL is chi-square distributed; thus, the likelihood ratio test was used to evaluate alternative models when models were nested with each other. The significance of a parameter was tested by fixing it to zero and by comparing the resulting model-fit statistics to those for the full model. Akaike's information criterion (AIC = −2LL − 2df; Akaike, 1987) and sample size adjusted Bayesian information criterion (BIC) were compared for alternative models when models were not

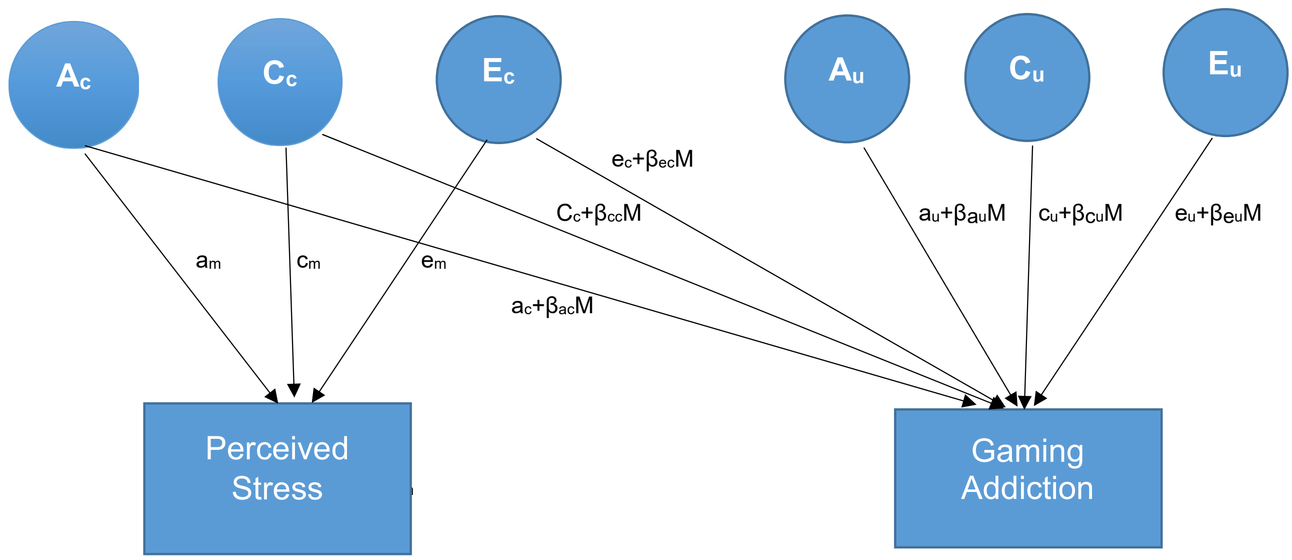

Fig. 1. Bivariate G x E model: The factors a_m, c_m, and e_m represent additive genetic influences, shared environmental influences, and non-shared environmental influences, respectively, on the moderator (M), the Perceived Stress (PS). The factors A_c, C_c, and E_c represent additive genetic influences, shared environmental influences, and non-shared environmental influences, respectively, shared between gaming addiction (GA) and PS. The factors A_U, C_U, and E_U represent the genetic, shared environmental influences, and non-shared environmental influences unique to GA. Interactions with the moderator (e.g., $\beta_{ac}M$) are added to these common and unique genetic influences and similar interactions are modeled for the shared and non-shared environmental paths. Please see the main text for further details

nested with each other. Models exhibiting lower AIC and BIC were considered more parsimonious and were thus preferred.

Ethics

The procedures of the current study were conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of Kookmin University, South Korea. All subjects were informed about the study and all provided informed consent. Parental consent was sought for those aged less than 18 years.

RESULTS

Descriptive statistics and twin correlations

Table 1 presents the descriptive statistics for GA and PS by sex and zygosity. There were significant sex differences in means for GA (males > females) and PS (females > males). Means and variances were significantly higher for MZ than for DZ twins in GA and PS. Although PS was relatively normally distributed (skewness = 0.57), GA was significantly skewed (skewness = 1.70). Thus, the scores of GA were log transformed (skewness = 0.40) and used for subsequent analyses. Consistent with the literature (Ropovik et al., 2023), the present sample showed a significant correlation between PS and GA [r = 0.53 (95% CI: 0.49, 0.57)].

For GA, MZ and DZ correlations were 0.72 (95%CI: 0.67, 0.76) and 0.36 (95%CI: 0.26, 0.46), respectively. Corresponding correlations for PS were 0.80 (95%CI: 0.76, 0.83) and 0.48 (95%CI: 0.39, 0.56), respectively. Significantly higher MZ than DZ twin correlations suggested strong genetic effects on both traits. Additionally, the DZ twin correlation for PS was higher than half that for MZ, which indicates the presence of shared environmental influences on PS. Non-shared environmental influences were modest as MZ twin correlations were high for PS and GA.

Univariate model-fitting analysis

Appendix Table A1 presents the goodness-of-fit statistics of the univariate model-fitting analysis for GA and PS, and Fig. 2 shows the parameter estimates in the best-fitting model. For GA, significant change in chi-square ($\Delta\chi^2_{(1)}$ = 39.1, p = 0.00) occurred when "A" was removed from the full model, but "C" could be dropped without significant change in chi-square ($\Delta\chi^2_{(1)}$ = 1.9, p = 0.17). Therefore, the AE model was chosen as the best-fitting model for GA,

Table 1. Means and standard deviations of gaming addiction (GA) and perceived stress (PS) by sex, zygosity, and birth order

	MZ	DZ[a]	p	Male	Female	p	1st	2nd	*p*
GA	8.41 (±11.40)	5.33 (±8.34)	<0.01	8.64 (±9.96)	6.38 (±10.62)	<0.01	7.12 (±10.43)	7.27 (±10.45)	0.78
PS	20.81 (±13.73)	18.87 (±10.99)	<0.01	19.30 (±12.34)	20.51 (±13.11)	<0.01	19.86 (±13.04)	20.28 (±12.65)	0.54

Note. [a] includes same-sex and opposite-sex twins. MZ = monozygotic twins, DZ = dizygotic twins. 1[st] = first-born twins, 2[nd] = 2[nd]-born twins.

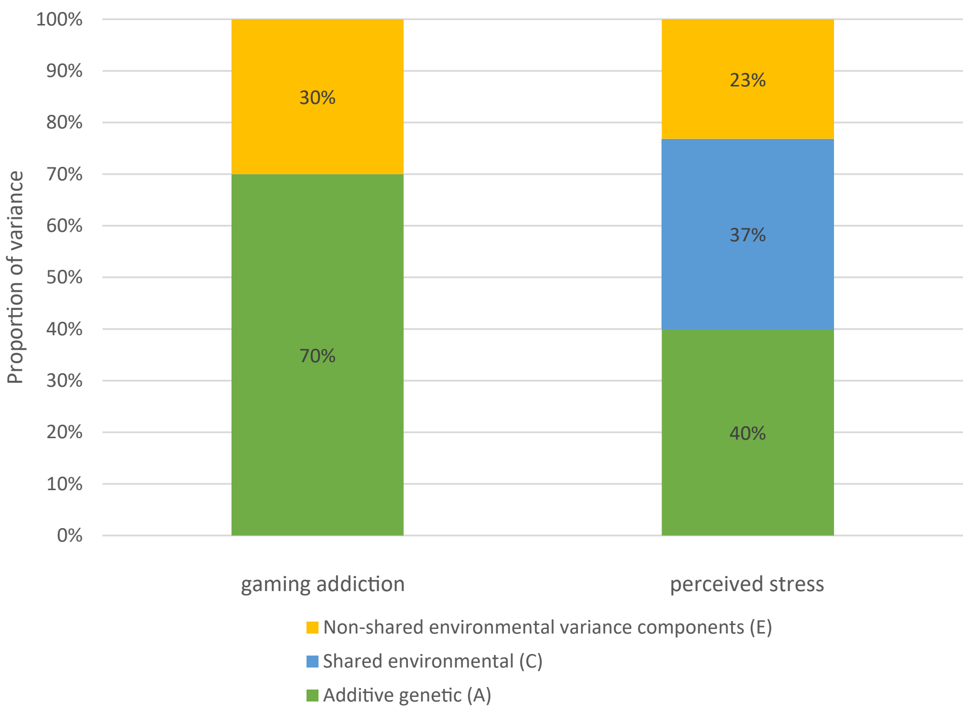

Fig. 2. Additive genetic (A), shared environmental (C), and non-shared environmental variance components (E) in the best-fitting univariate model. E includes measurement error

where "A" and "E" were, respectively, 0.70 (95%CI: 0.61, 0.77) and 0.30 (95%CI: 0.26, 0.33). For PS, neither "A" nor "C" could be dropped from the ACE model without significant change in chi-square ($\Delta\chi^2_{(1)} = 33.2$, $p = 0.00$; $\Delta\chi^2_{(1)} = 13.8$, $p = 0.00$). Thus, the ACE model was selected as the best-fitting one, "A", "C" and "E" for PS were 0.40(95%CI:0.25,0.58), 0.37(95%CI: 0.19, 0.51), and 0.23 (95%CI: 0.20, 0.27) respectively. Taken together, these results suggest that genetic and non-shared environmental influences were significant for GA and PS, but shared environmental influences were significant only for PS.

Bivariate G x E model-fitting analysis

Table 2 presents the results of the bivariate G x E model-fitting analysis. When all interaction parameters (i.e., β_{ac}, β_{au}, β_{cc}, β_{cu}, β_{ec} and β_{eu} in Fig. 1) were removed from the full model, a significant change in chi-square occurred ($\Delta\chi^2_{(6)} = 42.0$, $p = 0.00$) (model 2), which indicates the presence of G x E effects. When interaction parameters for "A" (β_{ac}, β_{au}), "C" (β_{cc}, β_{cu}), and "E" (β_{ec}, β_{eu}) were individually dropped from the full model (models 3–5), only the model without "A" (βac, βau) showed a significant change in chi-square ($\Delta\chi^2_{(2)} = 9.4$, $p = 0.01$) (model 3), indicating that PS moderates "A" but not "C" or "E" effects on GA. When the "A" interaction parameter unique to GA (model 7) and the "A" interaction parameter common to GA and PS (model 8) was further individually dropped, both models yielded significant chi-square changes. Thus, both of the "A" interaction parameters (β_{ac}, β_{au}) were retained in the model. In addition, "C" common to GA and PS (model 9) and "C" unique to GA (model 10) was individually eliminated, which produced a significant change in chi-square in model 9 ($\Delta\chi^2_{(5)} = 15.0$, $p = 0.01$), but not in model 10 ($\Delta\chi^2_{(5)} = 6.6$, $p = 0.25$). The elimination of the E parameter common to GA and PS further produced a significant change in chi-square ($\Delta\chi^2_{(6)} = 32.6$, $p = 0.00$) (model 11). Thus, the model with all "A" interaction parameters but not "C" unique to GA was selected as the best-fitting model (model 10).

Graphic presentation of the best-fitting model. Figure 3 shows the unstandardized "A", "C", and "E" variances of GA as a function of the PS in the best-fitting model. Furthermore, Appendix Fig. A1 depicts the standardized "A", "C", and "E" variances as a function of the PS. In the absence of PS (-2SD), "A", "C", and "E" variances for GA were all relatively small, but "A" alone rapidly increased with the increase in the levels of PS, resulting in greater genetic and total variance of GA at higher levels of PS (+2SD) (Fig. 3). Across the levels of the PS, "C" and "E" variances for GA were small and constant, which suggests that genetic and not environmental factors are responsible for the increased total variance of GA at higher levels of PS. In terms of relative influences (i.e., standardized variance), similar to the unstandardized variance, "A" increased with increasing levels of PS, whereas "C" and "E" decreased (Appendix Fig. A1). These patterns supported the diathesis-stress model explaining the relationship between GA and stress, which suggests that stressful environments activate genetic influences on GA, leading to higher GA at higher levels of stress.

Table 2. Goodness-of-fit statistics of the bivariate gene by environment interaction (G x E) model-fitting analysis for the relationship between gaming addiction (GA) and perceived stress (PS)

Model		Goodness-of-fit statistics						
		−2LL	AIC	BIC	df	Δx^2	Δdf	*p*
1	Full G x E model	6,962.4	1,172.4	−1,462.0	2,895			
2	Drop all interaction parameters (β_{ac}, β_{au}, β_{cc}, β_{cu}, β_{ec} & β_{eu})	7,004.4	1,202.4	−1,451.2	2,901	42.0	6	0.00
3	Drop all A interaction parameters (β_{ac}, β_{au})	6,971.8	1,177.8	−1,460.7	2,897	9.4	2	0.01
4	Drop all C interaction parameters (β_{cc}, β_{cu})	6,965.5	1,171.5	−1,463.8	2,897	3.1	2	0.21
5	Drop all E interaction parameters (β_{ec}, β_{eu})	6,965.0	1,171.0	−1,464.1	2,897	2.6	2	0.27
6	Drop all C and E interaction parameters (β_{cc}, β_{cu}, β_{ec}, β_{eu})	6,968.8	1,170.8	−1,465.6	2,899	6.4	4	0.17
7	Drop all C and E interaction parameters and A interaction parameter unique to GA (β_{au}, β_{cc}, β_{cu}, β_{ec} & β_{eu})	6,987.4	1,187.4	−1,458.0	2,900	25.0	5	0.00
8	Drop all C and E interaction parameters and A interaction parameter common to GA & PS (β_{ac}, β_{cc}, β_{cu}, β_{ec} & β_{eu})	6,974.3	1,174.3	−1,464.6	2,900	11.9	5	0.04
9	Drop all C and E interaction parameters and C effects common to GA and PS (C_c, β_{cc}, β_{cu}, β_{ec} & β_{eu})	6,977.4	1,177.4	−1,463.0	2,900	15.0	5	0.01
10	**Drop all C and E interaction parameters and C unique to GA (C_u, β_{cc}, β_{cu}, β_{ec} & β_{eu})**	**6,969.0**	**1,169.0**	**−1,467.2**	**2,900**	**6.6**	**5**	**0.25**
11	Drop all C and E interaction parameters, C unique to GA, and E common to GA and PS (E_c, C_u, β_{cc}, β_{cu}, β_{ec} & β_{eu})	6,995.0	1,193.0	−1,455.9	2,901	32.6	6	0.00

Note. A = additive genetic effects, C = shared environmental effects, E = non-shared environmental effects and measurement error. −2LL = −2 log likelihood, AIC = Akaike Information Criterion, BIC = sample size adjusted Bayesian Information Criterion. The best-fitting model is indicated in bold.

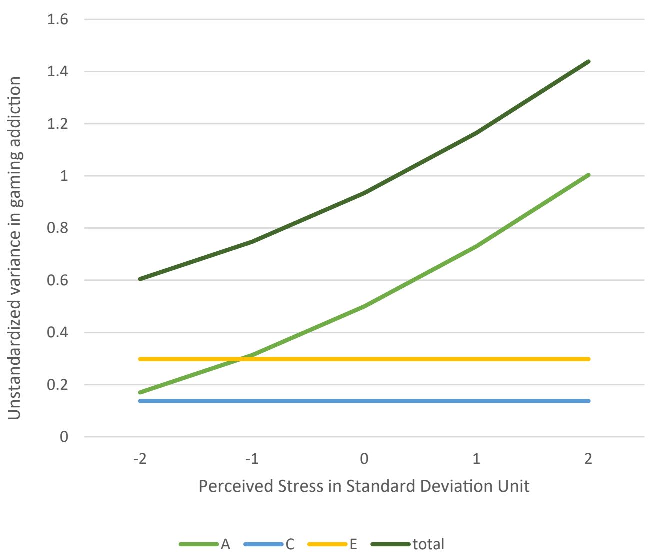

Fig. 3. Unstandardized additive genetic (A), shared environmental (C), non-shared environmental (E), and total variance components in gaming addiction as a function of perceived stress in the standard deviation unit

DISCUSSION

Using twins, the present study demonstrated significant genetic influences on GA (70%) and PS (38%), consistent with prior twin studies (e.g., Li et al., 2014; Vink et al., 2015). In addition, PS showed significant shared environmental effects (35%), which is not surprising because PS measured family stresses (family conflicts, family financial difficulties) as well as personal stresses (Academic performance, future career, friendship). These results were consistent with those found from other twin studies of stressful life events (e.g., Bemmels, Burt, Legrand, Lacono, & McGue, 2008) and a subsample of the present study (Jo & Hur, 2024). The results of the bivariate G x E model-fitting analyses showed that genetic variance of GA progressively increased with the increase in PS, supporting the diathesis-stress model, consistent with other twin studies of G X E for substance use (Hicks et al., 2009; Harden, Hill, Turkheimer, & Emery, 2008).

Twin studies elucidating the moderating role of stress in psychopathology have suggested different patterns of G X E effects. The diathesis-stress model suggests that stressful environments enhance expression of genetic risk for psychopathology, whereas the bio-ecological model posits that deleterious environments amplify environmental influences on psychopathology. While the two models are competing conceptualizations of G x E effects, generally, twin studies tend to support the bioecological model for childhood psychopathology and the diathesis-stress model for psychopathology in late adolescents and adults (Burt, 2015). The reason for the shift across development is that the bio-ecological model accentuates shared environmental factors that are more influential during childhood, whereas the diathesis-stress model emphasizes genetic liability that begins to increase during adolescence, when shared environmental influences diminish (Burt, 2015). Burt and Klump (2014) studied children aged 6–10 years and found that shared environmental influences on conduct problems were much larger with high levels of parent–child conflict as compared with those with low levels. Genetic influences, by contrast, were more influential at lower levels of conflict than at higher levels. As with the Dash et al. study (2023) mentioned earlier, the results were consistent with the bio-ecological model. It is likely that the present study supported the diathesis-stress model because the sample comprised late adolescents and young adults. The diathesis-stress model of G X E has also been observed molecular genetic studies for psychopathology. Using polygenic risk score (PRS) approach that weights and aggregates the effects of all genes into a single index of overall genetic risk, Meyers et al. (2019) showed that higher PRS was associated with a greater likelihood of cannabis use, but PRS only influenced cannabis use among those exposed to trauma, confirming the diathesis-stress model of G X E.

Clarifying the G X E mechanism for the relationship between stress and GA is important because it suggests future research directions and provides insights for development of optimal methods of prevention and intervention. The diathesis-stress model found in this study suggests a need to conduct genome-wide association studies to identify genes for GA in the future. Another valuable next research step is to examine how other environmental variables such as parental monitoring, peer influences, and school environment interact with genetic risk for GA. The pattern of G X E can vary across environmental variables. Given the importance of genetic liability found in this study, family members of individuals with GA such as siblings should be targeted for prevention. Stress management skills may have to be taught early to such siblings. Also, to maximize intervention effects, different rather than universal treatments should be given to individuals with and without genetic vulnerability to GA.

Limitations and conclusions

The current results should be interpreted with consideration of some limitations. First, to increase statistical power, we conducted model-fitting analyses based on a combined sample of males and females. However, given the sex differences in means of GA and PS (Kendler, Thornton, & Prescott, 2001; Mihara & Higuchi, 2017), future studies should explore sex differences in G x E effects in the relationship between stress and GA. Second, interestingly, the means and variances of GA and PS were larger for MZ than for DZ twins in the present sample. Carey (1992) suggested that these differences for heritable traits may constitute evidence for sibling interaction. That is, MZ twins may influence each other more than do DZ twins. Future twin studies of gaming behavior should explore sibling interaction effects and special twin environment by including regular sibling pairs. Third, although the present study utilizes genetically informative design to detect G X E effects, it is a cross-sectional study. The GX E effects can be best discovered in longitudinal studies, which incorporates the temporal relationship between environmental exposures and outcomes, and examines within-person changes (Dick & Kendler, 2012). Thus, longitudinal studies should be conducted in the future to confirm the present findings. Finally, although twins were recruited nationwide, the majority were primarily university students. This characteristic of the sample limits the generalizability of the findings. Another aspect that limits generalizability is that the sample only comprised South Koreans. Thus, caution is required when generalizing the results of this study to other populations.

Despite these limitations, the present findings contributed to the literature by providing empirical evidence of G x E effects for explaining the relationship between stress and GA. The findings may guide the development of prevention and intervention strategies for GA, and be used as a framework for future research.

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Authors' contribution: Not applicable.

Conflict of interest: The author declares that she has no competing financial interests.

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Appendix

Table A1. Results of univariate model-fitting analysis for gaming addiction (GA) and perceived stress (PS)

Measure	Model	Goodness-of-fit statistics							Parameter estimates		
		−2LL	AIC	BIC	df	Δx^2	Δdf	*p*	A	C	E
GA	ACE	3,784.2	868.2	−603.4	1,458				0.55 (0.36, 0.75)	0.14 (0.00, 0.33)	0.30 (0.26, 0.34)
	AE	**3,786.1**	**868.1**	**−604.2**	**1,459**	**1.9**	**1**	**0.17**	**0.70 (0.61, 0.77)**	–	**0.30 (0.26, 0.33)**
	CE	3,823.3	905.3	−585.6	1,459	39.1	1	0.00	—	0.60 (0.52, 0.69)	0.40 (0.36, 0.44)
PS	**ACE**	**3,591.7**	**675.7**	**−699.7**	**1,458**				**0.40 (0.25, 0.58)**	**0.37 (0.19, 0.51)**	**0.23 (0.20, 0.27)**
	AE	3,605.5	687.5	−694.5	1,459	13.8	1	0.00	0.77 (0.73, 0.80)	–	0.23 (0.20, 0.27)
	CE	3,624.9	706.9	−684.7	1,459	33.2	1	0.00	–	0.70 (0.66, 0.73)	0.30 (0.27, 0.34)

Note. A = additive genetic effects, C = shared environmental effects, E = non-shared environmental effects and measurement error. −2LL = −2 log likelihood, AIC = Akaike Information Criterion, BIC = sample size adjusted Bayesian Information Criterion. The best-fitting model is indicated in bold.

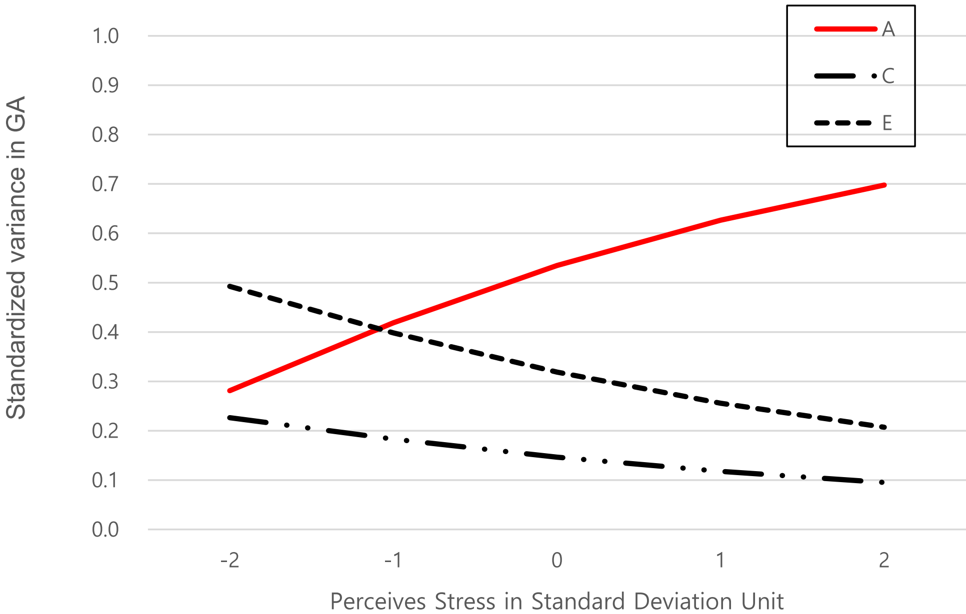

Fig. A1. Standardized variance components: Proportions of additive genetic (A), shared environmental (C), and non-shared environmental variances including measurement error (E) in gaming addiction (GA) as a function of perceived stress in the standard deviation unit