Prevention Science
https://doi.org/10.1007/s11121-022-01486-x

The Diffusion of Smoking: Association Between School Tobacco Policies and the Diffusion of Adolescent Smoking in 38 Schools in 6 Countries

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Accepted: 20 December 2022

Abstract
Social network research has evidenced the role of peer effects in the adoption of behaviours. Little is known, however, about whether policies affect how behaviours are shared in a network. To contribute to this literature, we apply the concept of diffusion centrality to school tobacco policies and adolescent smoking. Diffusion centrality is a measure of centrality which refers to a person's ability to diffuse a given property—in our case, smoking-related behaviours. We hypothesized that stronger school tobacco policies are associated with less diffusion centrality of smoking on school premises and of smoking in general. A whole network study was carried out in 2013 and 2016 among adolescents ($n = 18{,}805$) in 38 schools located in six European cities. Overall, diffusion centrality of smoking in general and of smoking on school premises significantly decreased over time. Diffusion centrality of smoking significantly decreased both in schools where the policy strengthened or softened over time, but for diffusion of smoking on school premises, this decrease was only significant in schools where it strengthened. Finally, stronger school tobacco policies were associated with lower diffusion centrality of smoking on school premises and of smoking in general, though to a lesser extent. With such policies, smoking may, therefore, become less prevalent, less popular, and less clustered, thereby lowering the risk of it spreading within networks in, and even outside the school.

Keywords Social network analysis · Diffusion centrality · Whole network design · Adolescent behaviour · Smoke-free policy · Key players

Introduction

Adolescents tend to adopt behaviours and attitudes that are similar to those of their peers (Brechwald & Prinstein, 2011), either through selection or influence processes (Maxwell, 2002; Osgood et al., 2015). As an example of selection process, Osgood et al. (2015) reported that adolescents were 1.6 times more likely to befriend someone who smoked if they smoked themselves, rather than befriend someone who did not smoke. As an example of influence process, Maxwell (2002) looked at two points in time and reported that adolescents were 1.7 times more likely to smoke at T2 if their friend had reported smoking at T1. The importance of peer effects has been highlighted in various areas of research, such as economic decision-making (Bollinger & Gillingham, 2012; Inhoffen et al., 2019), criminal activity (Bayer et al., 2009; Zimmerman & Messner, 2011), physical activity (Ali et al., 2011; Long et al., 2017), and risky health behaviours (Ali & Dwyer, 2009; An, 2015; Ennett et al., 2006; Fletcher,

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Published online: 18 January 2023

2010; Fujimoto & Valente, 2012; Go et al., 2012; Jeon & Goodson, 2015; Lakon et al., 2015; Lorant & Tranmer, 2019; Lundborg, 2006; Nakajima, 2007; Pollard et al., 2010; Robalino & Macy, 2018; Schaefer et al., 2012; Veenstra et al., 2013). They help us to understand how behaviours (e.g. depressive symptoms, aggressive behaviours, eating habits) and attitudes (e.g. academic motivation, body image) are shared in a network (Brechwald & Prinstein, 2011). They may also magnify the impact of policy interventions: an intervention may have a direct effect on the individuals who are impacted by the intervention in itself, but it may also have a spillover effect, as these individuals' behaviours impact other individuals around them (Cutler & Glaeser, 2010; Fletcher, 2007). These other individuals were, therefore, not directly impacted by the intervention in itself, but are eventually, indirectly impacted, through social interactions with those who were directly impacted. This indirect effect, also known as a social multiplier, may amplify the direct effect of policy interventions (Duarte et al., 2014), whether these policy interventions are environmental (e.g. climate policy regarding carbon taxation (Konc et al., 2021)), social (e.g. school-based intervention to lower violence (Yarnell et al., 2014)), or health interventions in different areas, such as sexual behaviour (Fletcher, 2007), blood donation (Bruhin et al., 2020), and smoking (Nikaj, 2017). Although social network research has made significant progress in understanding the role of peer effects in the adoption of behaviours and attitudes, few studies have looked at how the potential impact of policies could be increased by this social multiplier effect. To contribute to this literature, this study focuses on school tobacco policies and adolescent smoking, an area in which peer effects are known to be significant (Simons-Morton & Farhat, 2010), and in which there is increasing pressure to reduce adolescent smoking through the use of such policies.

Powell et al. (2005) showed that tobacco control policies, such as school smoking bans, may benefit from such indirect effects. School tobacco policies have a "legitimate role in 1) expressing the school's and community's norms and expectations […], 2) explicitly defining the punishments for violating these norms and expectations, 3) reinforcing those who comply with these norms and expectations, and 4) pressuring those who would not otherwise comply with these norms" (Goodstadt, 1989, p.249). In recent decades, school tobacco policies have been implemented to limit smoking at school. Countless studies have tested their effectiveness: stronger policies have been shown to be associated with less smoking on school premises (Adams et al., 2009; Kuipers et al., 2015; Lipperman-Kreda et al., 2009; Mélard et al., 2020; Watts et al., 2010), but not with less smoking in general (Kuipers et al., 2015; Lovato et al., 2010; Mélard et al., 2020).

There is, however, a lack of research regarding the effects of policies on how smoking is shared in a network, which could capture their social multiplier effect. Some studies have yet gone some way towards enhancing the importance of considering changes in the social structure. Christakis and Fowler (2008) analysed from 1971 to 2003 the evolution of the structural position of adults who smoked in the Framingham community. Their data did not enable them to draw conclusions about the potential impact of policy changes or of underlying mechanisms such as changes in the social acceptability of smoking. They did find, however, that smoking prevalence decreased over time, mostly due to the person-to-person spread of smoking cessation (Christakis & Fowler, 2008). Moreover, adults who smoked were more likely to become peripheral in friendship networks in that community (Christakis & Fowler, 2008). More recently, Osgood et al. (2013) analysed the effects of a school-based preventive intervention on adolescents' friendship networks. They found that, where the intervention took place, adolescents with antisocial behaviours (based on substance use, attitudes towards substance use and delinquent behaviour) were less central than others (Osgood et al., 2013). They suggested that the networks "changed in a way that should reduce diffusion of problem behaviours", further implying a social multiplier effect (Osgood et al., 2013, p.178).

The literature on peer effects has shown that popular peers have a stronger influence on smoking behaviour than unpopular peers (Robalino & Macy, 2018). Through their numerous connections, popular adolescents are more likely to diffuse norms that reinforce or sanction smoking (Alexander et al., 2001; Valente & Davis, 1999). They are also, however, more likely to conform to group norms, so their behaviour will also correspond strongly to the norms shared by most adolescents in the school (Alexander et al., 2001). One may therefore suppose that, in a school with a strong tobacco policy, in which the group norms would progressively shift towards disapproval of smoking, popular adolescents would rather comply with the school's norms and expectations. They would, in turn, diffuse, intentionally or unintentionally, norms that are unsupportive of smoking, reducing the power of peer effects in the adoption of smoking.

Common centrality indices, however, such as network measures of popularity, do not take into account the attributes (such as having a sexually transmittable disease, having a positive attitude towards a political candidate, or reporting substance use) of each individual (hereafter ego) in the network or how those attributes diffuse through the network (Kang et al., 2012). For instance, an ego might be central in terms of the spread of support for a political party, but not in terms of the spread of support for conserving endangered species (Kang et al., 2012). Studies have therefore come up with another measure of centrality: diffusion centrality

(Banerjee et al., 2013; Kang et al., 2012), which is defined as a person's "ability to diffuse a given property" (Kang et al., 2012, p.558). Unlike standard centrality measures, which identify central leaders, diffusion centrality identifies the most diffusive ones, i.e. those with greater potential to diffuse a given attribute, in our case: smoking.

Measuring the diffusion centrality captures the centrality of a behaviour at a network level. Taking the network level into account is especially useful when looking at a social behaviour like smoking, for which peer influence is key. A research based on part of the data used in the present study evaluated to what extent smoking, among other behaviours, varied at the individual, peer, and school level (Lorant & Tranmer, 2019). The authors found that the school level explained very little of the variance in smoking, while the peer network accounted for half of the variance, suggesting that smoking is best addressed at the peer-network level. After studying the relationship between school tobacco policies and the individual behaviour of smoking in another paper (Mélard et al., 2020), we will use the same data to look at this relationship at a network level.

For a long time, there has been an international trend towards policies restricting smoking. The present study provides new insights into the impact of such policies on the centrality of a behaviour in a network, using the diffusion centrality as an outcome. It aims to examine the relationship between school tobacco policies and the diffusion centrality of adolescent smoking. We hypothesize that stronger school tobacco policies are associated with lower diffusion centrality of smoking on school premises and of smoking in general. We also compare these measures of diffusion centrality to popularity, a more common centrality measure. This study is unique due to its diversity of policy contexts: it encompasses two points in time and schools in six countries with different national tobacco regulations (Joossens & Raw, 2006, 2017) and heterogeneous implementations of school tobacco policies (Mélard et al., 2020). It therefore offers great variance across policies, both longitudinally and transversely.

Methods

Design and Study Population

This study is based on data from the SILNE and SILNE-R (Smoking Inequalities – Learning from Natural Experiments) social network surveys with a whole network design (Lorant et al., 2015). Data were collected in six European cities in six countries (Namur in Belgium, Tampere in Finland, Hanover in Germany, Latina in Italy, Amersfoort in the Netherlands, and Coimbra in Portugal), with different national tobacco regulations (Joossens & Raw, 2006, 2017) and different school tobacco policies (Mélard et al., 2020). The cities selected were representative of their countries in terms of average income. Lorant et al. (2015) provide more information on the selection of cities and schools. Ethical approvals were obtained in each city and updated for the second data collection (Lorant et al., 2015) (see Ethics approval).

Data collections took place in 38 schools between January and November 2013 and between September 2016 and October 2017. In total, 18,502 adolescents in grades corresponding to ages 14–16 participated: 9305 adolescents in 2013 (response rate: 85%) and 9197 other adolescents in 2016 (response rate: 81%). They completed a self-administered paper and pencil questionnaire during school hours, in which they were asked about their smoking behaviour, smoking norms, socio-economic status, and other information about their health status, family, and school environment. The survey included a name generator based on the ego's friends in the same two grades. Adolescents were handed a directory listing the names of their schoolmates. They were asked "Who are your best and closest friends?" and could cite up to five friends (see Lorant et al. (2015) for more information on the methodology).

Measurements

Diffusion Centrality Measure

We used Banerjee et al.'s (2013) definition of "the diffusion centrality of a node i in a network with an adjacency matrix g, passing probability q, and iterations T, as the ith entry of the vector $DC(g;q,T) := \left[\sum_{t=1}^{T}(qg)^t\right] \bullet 1$." (Banerjee et al., 2013, p. 6).

In this section, we outline how we defined the different parameters applied to our case. The g matrix is the transposed adjacency matrix, so cell g_{ij} corresponds to the citation received by i from j. We did this because the aim was to look at who could potentially be influenced by node i's behaviour (Christakis & Fowler, 2008; Hall & Valente, 2007). The matrix q is a diagonal matrix containing probabilities. More precisely, q_{ii} is the probability that node i has a given attribute, i.e. whether node i reported smoking in general and smoking on the school premises. The construction of the probability matrix q is explained below. We computed diffusion centrality as the sum at the first (friends), second (friends of friends), and third indegree separation (friends of friends of friends). Second and third indegree separations were obtained by raising the transposed adjacency matrix g to the power of 2 (iterations $T=2$) and 3 (iterations $T=3$), respectively (Wasserman & Faust, 1994). We subtracted the diagonal of $(qg)^t$ to avoid two-step and three-step cycling (Wang & Strret, 2015). We obtained two measures of diffusion centrality for each adolescent: the measure of diffusion centrality of smoking in general translated this adolescent's ability to diffuse their smoking behaviour, while the measure of diffusion centrality of smoking on school premises

translated their ability to diffuse their behaviour of smoking specifically on school premises. Because adolescents who have never smoked are not likely to diffuse smoking to people around them, they were taken into account to compute the diffusion centrality measures, but were not included in the analyses. Aggregating these individual measures of diffusion centrality enables us to conclude on the diffusion centrality of these behaviours in the network. An illustration of the diffusion centrality is provided after detailing the design of the probability matrix and the other network measures.

Construction of the Probability Matrix *q*

The probability matrix *q* was computed for two smoking outcomes: smoking and smoking on school premises. Smoking was measured using the question: "How many cigarettes have you smoked during the last 30 days?" Adolescents were given a score on a 4-point scale depending on their level of smoking, which we recoded to probabilities of diffusing smoking (0.15: never smoked; 0.4: has not smoked in the last 30 days; 0.6: has smoked 1–2 cigarettes in the last 30 days; 0.75: has smoked at least weekly in the last 30 days; 0.85: has smoked at least daily in the last 30 days). We attributed values greater than 0 and less than 1, to avoid using 0 in the calculations because of its multiplication property, i.e. would block the diffusion, and 1 which would amplify the influence at the 2nd- and 3rd-degree friendship (matrix to the power of 2 and of 3). We attributed values that take into account the distance between the levels of smoking: the difference in probabilities of diffusing smoking between an adolescent who never smoked and one who ever smoked is greater than between one who reported smoking weekly or smoking daily.

Smoking on school premises (0: no; 1: yes) was assessed among adolescents who reported having smoked at least one cigarette over the last 30 days. We recoded these items to probabilities 0.15 and 0.85, respectively, to, again, avoid the extremes 0 (would block the diffusion) and 1 (would amplify too much). Due to a translation error in the survey, Portuguese data had to be excluded from the analyses of smoking on school premises.

Other Network Measures

To describe our networks, we computed different network measures. To measure adolescents' popularity, we used indegree centrality, i.e. the number of citations an individual gets from alters (Borgatti et al., 2018). We also computed the closeness centrality which is the distance between an individual and all other individuals in the network. It is an inverse measure of centrality: the greater the distance is, the more peripheral they are (Borgatti et al., 2018). Moreover, to reflect on the clustering of individuals according to their smoking behaviour, i.e. adolescents who smoke connected to other adolescents who smoke, we calculated the Coleman homophily and the E-I indices [−1; 1] (Bojanowski & Corten, 2014). The Coleman homophily index ranges from −1 (perfect heterophily) to 1 (perfect homophily) and takes the value 0 when the observed number of within-group ties corresponds to the expected number of within-group ties in a random network. The E-I index is the difference between external ties and internal ties, ranges from −1 (all ties are internal to the groups) to 1 (all ties are external to the groups), and takes the value 0 if the ties are equally divided (Krackhardt & Stern, 1988).

Illustration of the Diffusion Centrality of Smoking

Figure 1 shows how diffusion centrality (DC) may vary according to the smoking status and popularity of an adolescent, as well as the smoking status and popularity of the adolescent's friends. In all situations, adolescents who do not smoke, although they may have high scores in more common centrality measures, have a null diffusion centrality; i.e. they are not likely to diffuse smoking. This figure illustrates the added value of the measure of diffusion centrality, whereby both the smoking status and the

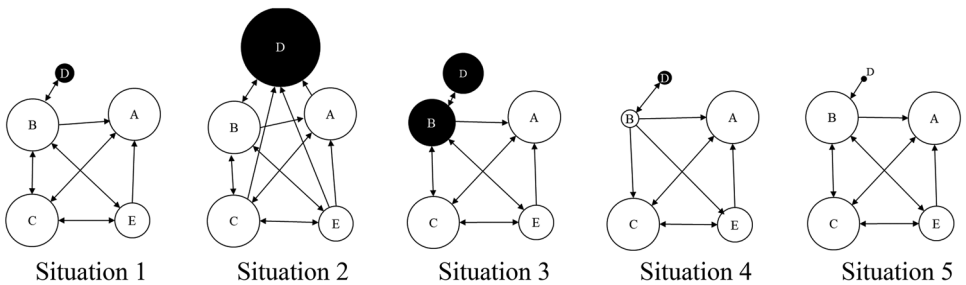

Fig. 1 Example graphs. Size of nodes varies according to diffusion centrality of smoking for adolescents who reported that they smoked at least once a week (in black, here *D* in all situations and *B* in situation 3) and by indegree for those who had never smoked (in white). The direction of the arrows shows the direction of citation (friendship). Adolescents who never smoked automatically have a null diffusion centrality of smoking

topology of the network are taken into account. An adolescent who reports that they smoke might have a higher or lower diffusion centrality depending on their popularity, but also depending on their friends' smoking status and popularity, corresponding to the influence they may have on the rest of the network through these friendships. All the situations in Fig. 1 illustrate a network of five adolescents, of which *D* always reports smoking at least once a week. The arrows represent the connections (or ties) between each adolescent, and the direction of each arrow shows the direction of each citation. In situation 1, *D* is not very popular. They have one sole connection to *B*, who is, on the contrary, quite popular and is the bridge, i.e. sole connection, between *D* and the rest of the network. In situation 2, *D* is more popular. In situation 3, *D* is as peripheral as in situation 1. They have only one connection to *B*, but this time *B* also reports smoking. Situation 4 is similar to situation 1. *D* has a connection to *B*, who does not smoke, but *B* is not as popular any more. Finally, situation 5 is similar to situation 1, but *D* is a pendant, i.e. unreciprocated connection to *B* (*D* cited *B* but *B* did not cite *D*). The diffusion centrality translates how central an adolescent is to the diffusion of smoking to the other nodes. In this case, the adolescent who is the most likely to diffuse smoking is node *D* in situation 2 (DC = 4.53), who reports smoking and is the most popular (indegree = 4). In situations 1, 3, and 4, *D* has an indegree of 1, but has a lower diffusion centrality in situation 4 (DC = 0.75) than in situation 1 (DC = 1.06) as *D* is friends with *B*, who is less popular in situation 4 than in situation 1. Moreover, *D* has a higher diffusion centrality in situation 3 (DC = 2.30) than in situations 1 and 4 as *D* is friends with *B*, who also reports smoking and has an indegree of 3. This situation illustrates the clustering of smoking. Finally, in situation 5, node *D* has a null diffusion centrality even though they smoke, because they have an indegree of 0, i.e. *D* is not likely to influence anyone around them (see Supplementary material A for detailed calculations of situations 1 and 3 of Fig. 1).

School Tobacco Policies

We used a score to measure school tobacco policies (STP), which is detailed elsewhere (Mélard et al., 2020). It is a 10-point score calculated at the school level that consider their multidimensionality (comprehensiveness, enforcement, and communication of the policy), and the perceptions of both students and staff. It provided a suitable measure, therefore, for evaluating the policy in each school from our sample. Schools with a higher score have in place a policy which is comprehensive (applied to students, staff and visitors, at all time and everywhere in the school premises), well enforced (there are sanctions in case of rule infringement and these sanctions are well thought-off), and well communicated (students, staff and visitors are well aware of the policy and it is formally communicated). Such environments should therefore discourage smoking, reducing the diffusion potential of adolescents who smoke.

Potentially Confounding Variables

We used the adapted MacArthur scale (youth version) to measure the subjective social status of the adolescents (Goodman et al., 2001). They were asked to rank their family's social status on a 10-step ladder that represented their country society: "Imagine that this ladder shows how your country society is made up. At the top of the ladder are the people who are the best off – they have the most money, the highest level of education, and the jobs that bring the most respect. At the bottom of the ladder are the people who are the worst off –they have little or no education, no jobs, or jobs that don't pay much. Now think about your family. Please tell us where you think your family would be on this ladder." We then classified adolescents into four groups according to the distribution percentiles: low (5th step and lower), middle low (6th step), middle high (7th step), and high (8th step and higher). To measure parental smoking, adolescents reported having either no, one, or two or more (step-)parent(s) who smoked. Year, gender, and age were also factored in.

Statistical Analyses

Pearson's chi-square tests and Student's *t*-tests were used to describe our sample and check for significant differences between 2013 and 2016. We then conducted various multilevel mixed regression analyses (individual level and school level). Given the skewed distributions of diffusion centrality of smoking and of school premises (see Supplementary material B), we used log $(x+1)$ to prevent potential issues with heteroscedasticity (adding a value of 1 was necessary to avoid null values for diffusion centrality). First, we examined the association between diffusion centrality of smoking (dependent variable) and STP score (independent variable). In all models, we controlled for the year of data collection. In the first model, we included the STP score. In the second model, we controlled for age, gender, socio-economic status, and parental smoking. Then, we replicated the analyses to examine the association between diffusion centrality of smoking on school premises (dependent variable) and STP score (independent variable). Our findings were not sensitive to different coding schemes of the variables used to construct the probability matrix *q* (see Supplementary material C for the sensitivity analyses). Finally, in order to compare our analyses of diffusion centrality with a more common measure of centrality, we conducted similar analyses with indegree as the dependent variable. To compare the indegree with the diffusion centrality of smoking, we performed the analysis among adolescents who had smoked at least

once and those who smoked regularly. To compare indegree with diffusion centrality of smoking on school premises, we performed the analysis among adolescents who smoked on school premises. Analyses were conducted in SAS 9.3.

Results

Table 1 presents the characteristics of our sample in 2013 and 2016. In general, more adolescents reported having smoked at least once in 2013 (51.1% in 2013) than in 2016 (41.0% in 2016, $p < 0.0001$). Among adolescents who reported currently smoking, fewer reported that they smoked on school premises (39.7% in 2013 and 30.2% in 2016, $p < 0.0001$). Adolescents who reported that they smoked regularly (at least once a week) had similar indegree centrality to the other adolescents, and this remained stable between 2013 and 2016. Their closeness centrality increased over time and was higher than that of other adolescents in both years, meaning they were more peripheral. In both years, adolescents who reported smoking regularly were not likely to be homophilous, on the contrary to the other adolescents; i.e. adolescents who did not report smoking regularly were more likely to have friendship ties with other adolescents who did not report smoking regularly either. Between 2013 and 2016, the homophily of these adolescents increased (Coleman index = 0.57 in 2013 and 0.67 in 2016; E-I index = −0.70 in 2013 and −0.80 in 2016), while it further decreased for adolescents who reported smoking regularly (Coleman index = 0.13 in 2013 and 0.08 in 2016; E-I index = 0.06 in 2013 and 0.15 in 2016). At the school level, smoking prevalence decreased, while the mean STP score remained similar (6.0 in 2013 and 6.1 in 2016). Schools were, however, quite heterogeneous in that respect. In twenty-seven schools, the STP became stronger over time, with a median increase of 0.47 (0.04–2.03), while in eleven schools, the STP became weaker, with a median decrease of 0.65 (0.12–3.99).

Table 2 shows the evolution of diffusion centrality measures in 2013 and 2016 across levels of parental smoking, subjective social status, school smoking prevalence, STP scores, and changes in STP over time. Overall, the diffusion centrality of smoking and of smoking on school premises decreased significantly between 2013 and 2016 ($T = 3$). The diffusion centrality measure at $T = 1$ shows the average number of adolescents influenced at the first degree of friendship, with a certain weight depending on the smoking level of the influencer, i.e. whether the influencer has only tried smoking, smokes weekly, or smokes daily. This value was similar in both years for the diffusion centrality of smoking in general, but decreased significantly for the diffusion

Table 1 Evolution of the characteristics of the student sample ($n = 18{,}502$), SILNE-R study in six EU cities, 2013–2016

	2013 (%)	**2016** (%)	***p* value**[a]
Individual level (*N*)	9305	9197	
Smoking in the last 30 days			< .001
Never smoked	48.9	59.0	
Has not smoked	24.5	20.9	
Has smoked 1–2 cig	7.4	6.2	
Has smoked at least weekly	3.8	5.0	
Has smoked at least daily	15.5	9.0	
Smoking on school premises[b]	39.7	30.2	< .001
Indegree (mean, std)			
Smoke regularly	3.4 (2.2)	3.4 (2.2)	0.579
Otherwise	3.4 (2.1)	3.4 (2.1)	0.452
Closeness (mean, std)			
Smoke regularly	12.1 (5.0)	13.2 (6.5)	< .001
Otherwise	11.6 (4.7)	11.7 (5.4)	0.686
Coleman homophily [−1;1] (mean, std)			
Smoke regularly	0.13 (0.7)	0.08 (0.7)	0.038
Otherwise	0.57 (0.6)	0.67 (0.6)	< .001
Cities – Countries			< .001
Namur – Belgium	20.9	21.1	
Tampere – Finland	16.1	16.6	
Hanover – Germany	8.3	5.7	
Latina – Italy	21.4	21.6	
Amersfoort – the Netherlands	12.9	14.9	
Coimbra – Portugal	20.4	20.3	
Age (mean, std)	15.3 (1.1)	15.1 (1.0)	< .001
Male	47.3	50.0	< .001
Subjective social status			< .001
Low	23.7	26.6	
Middle low	19.1	18.5	
Middle high	27.0	25.2	
High	30.1	29.7	
Parental smoking			< .001
No parent smoking	53.0	55.9	
1 (step-)parent smoking	26.4	25.1	
2 + (step-)parents smoking	20.6	19.0	
School level (*N*)	38	38	
School smoking prevalence	19.1 (0.1)	14.3 (0.1)	0.044
STP score (0–10)[c]	6.0 (1.3)	6.1 (1.5)	0.699

[a] *p* values of differences between 2013 and 2016, calculated with Pearson's chi-square tests for categorical variables and Student's *t*-tests for continuous variables

[b] Among adolescents who reported smoking within the last 30 days, excluding Coimbra, where smoking on school premises was not measured ($n = 1832$ in 2013; $n = 1425$ in 2016)

[c] STP change (STP score in 2016 – STP score in 2013): median (min; max) = 0.0 (−4.0; 2.0)

Table 2 Evolution of diffusion centrality (DC) measures over time (mean, std), SILNE-R study in six EU cities, 2013–2016

	DC of smoking[a]			DC of smoking on school premises[b]		
	2013 ($n=4514$) Mean (std)	**2016** ($n=3528$) Mean (std)	***p* value**[c]	**2013** ($n=1863$) Mean (std)	**2016** ($n=1418$) Mean (std)	***p* value**[c]
Individual level						
$T=1$ (1st-degree friendship only)	2.0 (1.5)	2.0 (1.5)	0.056	1.4 (1.6)	1.2 (1.5)	< .001
$T=2$ (up to 2nd-degree friendship)	5.0 (4.7)	4.7 (4.5)	< .001	3.0 (4.3)	2.4 (3.8)	< .001
$T=3$ (up to 3rd-degree friendship)	10.1 (12.4)	9.0 (11.3)	< .001	5.1 (9.4)	4.0 (8.3)	< .001
Parental smoking						
No parent smoking	9.0 (10.3)	8.1 (10.1)	0.010	4.1 (7.1)	3.4 (7.1)	0.109
1 (step-)parent smoking	10.2 (12.1)	9.3 (12.0)	0.083	5.1 (8.9)	4.2 (9.2)	0.142
2 + (step-)parents smoking	11.6 (15.1)	10 (12.3)	0.007	6.1 (11.2)	4.4 (8.4)	0.002
Subjective social status						
High	10.4 (12.2)	9.5 (11.3)	0.087	4.0 (6.8)	3.6 (7.8)	0.466
Middle high	10.3 (11.7)	9.1 (11.6)	0.026	4.9 (7.8)	4.2 (8.9)	0.211
Middle low	10.4 (13.2)	9.2 (11.7)	0.071	6.1 (10.7)	4.6 (9.8)	0.081
Low	9.4 (12.8)	8.3 (10.8)	0.022	6.2 (12.5)	3.7 (7.0)	< .001
School level						
School smoking prevalence						
Low	8.4 (9.7)	6.7 (8.2)	< .001	3.3 (4.9)	2.5 (5.2)	0.064
Middle	9.1 (10.2)	8.6 (10.4)	0.129	4.2 (7.3)	3.4 (8.8)	0.119
High	12.0 (15.2)	10.4 (13.1)	0.001	6.6 (11.7)	4.7 (8.6)	< .001
STP score						
High	9.3 (10.5)	8.0 (10.3)	0.003	1.6 (2.4)	1.2 (0.8)	0.048
Middle	9.3 (12.1)	8.2 (10.5)	0.014	2.7 (5.2)	2.7 (6.1)	0.993
Low	11.4 (13.7)	10.3 (12.5)	0.024	7.5 (11.6)	5.2 (9.7)	< .001
STP change						
Decrease in 2016	9.7 (11.7)	8.2 (10.6)	0.002	3.3 (4.7)	3.1 (5.4)	0.644
Increase in 2016	10.3 (12.7)	9.3 (11.6)	0.002	5.9 (10.6)	4.3 (9.0)	< .001

[a]Among adolescents who ever smoked, $T=3$ (up to third-degree friendship)

[b]Among adolescents who smoked within the last 30 days, excluding Coimbra, $T=3$ (up to third-degree friendship)

[c]*p* values of differences between 2013 and 2016, calculated with Student's *t* tests

centrality of smoking on school premises. Subtracting the value at $T=1$ from the value at $T=3$ shows us the potential to influence friends of friends, with a smaller weight the more distant they are. In both years, diffusion centrality of smoking was lowest among less vulnerable adolescents: it was lowest among those with no parents who smoked, in schools with lower smoking prevalence, and in schools with higher STP scores. These results were similar for the diffusion centrality of smoking on school premises. Diffusion centrality of smoking decreased both in schools where the STP score increased and in schools where the STP score decreased between 2013 and 2016. For diffusion centrality of smoking on school premises, this decrease was only significant in schools where the STP score increased over time.

Table 3 presents the regression coefficients of diffusion centrality of smoking and of smoking on school premises according to STP score. The diffusion centrality of smoking decreased in 2016 compared to 2013. It was also lower when the STP scores were higher. This association remained significant, and the size effects were not altered when controlling for parental smoking and other confounding variables. The results for diffusion centrality of smoking on school premises went in the same direction, though with larger size effects: diffusion centrality of smoking on school premises was lower in 2016 and was associated with higher STP scores. That statistical significance and the size effect of the association remained when controlling for confounding variables.

Table 4 shows the regression coefficients of indegree according to STP score. In order to compare this measure with the diffusion centrality measures, as the indegree centrality does not take into account the smoking status, we used different samples: among adolescents who reported having smoked at least once, smoking regularly, and smoking on school premises. There was no decrease over time in the indegree of the

Table 3 DC of smoking and DC of smoking on school premises according to STP score (0–10), linear multilevel regression, mixed models: coefficient (95% confidence interval), SILNE-R study in six EU cities, 2013–2016

	DC of smoking[a, b]		**DC of smoking on school premises**[b, c]	
	Model 1 Beta (CI 95%)	Model 2 Beta (CI 95%)	Model 1 Beta (CI 95%)	Model 2 Beta (CI 95%)
Year (ref = 2013)	**−0.10 (−0.15; −0.06)**	**−0.09 (−0.14; −0.05)**	**−0.17 (−0.23; −0.10)**	**−0.15 (−0.22; −0.09)**
STP score (0–10 scale)	**−0.05 (−0.09; −0.02)**	**−0.05 (−0.09; −0.02)**	**−0.14 (−0.19; −0.09)**	**−0.14 (−0.19; −0.09)**
Parental smoking				
No parent smoking		ref		ref
1 (step-)parent smoking		**0.06 (0.01; 0.11)**		0.02 (−0.06; 0.09)
2 + (step-)parents smoking		**0.11 (0.06; 0.17)**		**0.12 (0.05; 0.19)**
Subjective social status				
High		ref		ref
Middle high		−0.04 (−0.09; 0.02)		0.03 (−0.05; 0.11)
Middle low		**−0.08 (−0.14; −0.01)**		0.03 (−0.06; 0.12)
Low		**−0.15 (−0.21; −0.08)**		−0.01 (−0.10; 0.07)
Gender (ref = female)		**−0.05 (−0.10; −0.01)**		−0.02 (−0.08; 0.05)
Age		**0.03 (0.00;0.05)**		**0.04 (0.01;0.07)**
Goodness of fit (AIC[d])	21,649.8	21,616.0	7,901.7	7,915.8
Covariance parameter estimate	**0.05 (0.03; 0.06)**	**0.04 (0.03; 0.06)**	**0.09 (0.06; 0.12)**	**0.09 (0.06; 0.12)**

Model 1: year and STP score included simultaneously, school as random effect. Model 2: model 1 controlling for parental smoking, socio-economic status, gender, and age

Significant coefficients are in bold

[a]Among adolescents who ever smoked

[b]Calculated at up to the 3rd-degree friendship (see the Methods section)

[c]Among adolescents who reported smoking within the last 30 days, excluding Coimbra

[d]*AIC* Akaike's information criteria

adolescents in any of those categories. Stronger STPs were significantly associated with lower indegree among those who reported having smoked at least once and among those who reported smoking on school premises, but not among those who reported smoking regularly. Low socio-economic status was associated with lower indegree among adolescents who had smoked at least once and among those who smoked regularly, but not among those who smoked on school premises.

Discussion

There is a need to understand whether policies affect how behaviours are shared in a network. We contribute to the literature by looking at school tobacco policies and adolescent smoking. Our findings showed that stronger policies were associated with lower diffusion centrality of smoking on school premises and that of smoking in general, though to a lesser extent. Previous research had rather focussed on the individual behaviour and had found that such policies were associated with less smoking on school premises (Adams et al., 2009; Kuipers et al., 2015; Lipperman-Kreda et al., 2009; Mélard et al., 2020; Watts et al., 2010), but the present study considers the network level and shows that such policies may benefit from a social multiplier effect. Moreover, we found that school tobacco policies may even have an impact outside of the school context. Although in the literature school tobacco policies were not found to lower smoking overall (Evans-Whipp et al., 2010; Kuipers et al., 2015; Mélard et al., 2020), our study found that stronger policies were associated with lower diffusion centrality of smoking in general. Thus, our evidence suggests that, with such policies in place, smoking may become less prevalent, less popular, and less clustered, thereby lowering the risk of it spreading within networks in and even outside the school.

We also found that adolescents with lower socio-economic status had lower diffusion centrality of smoking, which means that they had a lower potential to diffuse smoking. In theory, there are several possible explanations for the lower diffusion centrality of these adolescents: they smoke less, they are less popular, and/or they are less clustered than adolescents with higher socio-economic status. Recent research shows, however, that adolescents with lower socio-economic status are more likely to report that they smoke regularly

Table 4 Indegree according to STP score (0–10) among adolescents reporting having ever smoked, regularly smoking, and smoking on school premises, linear multilevel regression, mixed models: coefficient (95% confidence interval), SILNE-R study in six EU cities, 2013–2016

	Among adolescents having ever smoked	**Among adolescents regularly smoking**	**Among adolescents smoking on school premises**[a]
	Beta (CI 95%)	Beta (CI 95%)	Beta (CI 95%)
Year (ref = 2013)	−0.01 (−0.11; 0.08)	0.05 (−0.12; 0.22)	−0.04 (−0.32; 0.24)
STP score (0–10 scale)	**−0.09 (−0.16; −0.03)**	−0.06 (−0.15; 0.02)	**−0.19 (−0.33; −0.06)**
Parental smoking			
No parent smoking	ref		
1 (step-)parent smoking	−0.02 (−0.13; 0.10)	0.00 (−0.21; 0.21)	−0.09 (−0.44; 0.27)
2 + (step-)parents smoking	−0.09 (−0.20; 0.03)	−0.08 (−0.28; 0.12)	−0.17 (−0.50; 0.16)
Subjective social status			
High	ref		
Middle high	−0.01 (−0.14; 0.12)	0.00 (−0.22; 0.22)	−0.10 (−0.46; 0.26)
Middle low	−0.04 (−0.18; 0.10)	0.01 (−0.24; 0.25)	0.20 (−0.21; 0.60)
Low	**−0.23 (−0.36; −0.09)**	**−0.31 (−0.54; −0.09)**	−0.23 (−0.60; 0.14)
Gender (ref = female)	0.02 (−0.08; 0.12)	0.02 (−0.16; 0.19)	0.10 (−0.19; 0.38)
Age	**−0.17 (−0.23; −0.12)**	**−0.20 (−0.28; −0.12)**	**−0.17 (−0.31; −0.03)**
Goodness of fit (AIC[b])	33,475.7	12,146.6	4,540.4
Covariance parameter estimate	**0.11 (0.07; 0.14)**	**0.07 (0.04; 0.11)**	0.03 (−0.02; 0.08)

Year and STP score included simultaneously, school as random effect, controlling for parental smoking, socio-economic status, gender, and age

Significant coefficients are in bold

[a]Among adolescents who reported smoking within the last 30 days, excluding Coimbra

[b]*AIC*, Akaike's information criteria

(Lorant et al., 2016; Shackleton et al., 2019). Moreover, they are also more likely to have more friends who report that they smoke, leading to much clustering of adolescents who smoke (Lorant et al., 2016). On the contrary, our findings showed that adolescents with lower socio-economic status had lower indegree centrality, meaning they were less popular overall than adolescents with higher socio-economic status. Using a sample of personal networks, Bidart et al. (2018) showed that young adults of lower educational status formed networks with different social structures than those with higher levels of education. The lack of popularity of adolescents of lower socio-economic status may explain their lower diffusion centrality, at least in their school network.

Another finding was that the diffusion centrality of smoking decreased over time. So, on top of the potential effect of school policies, smoking may have become less prevalent, less popular, and less clustered overall, reducing its potential to spread in the network. This is consistent with the other, more common, network measures that were computed: over time, adolescents who reported smoking regularly were less central and less clustered in the network. This shows that, aside from the policies that exist at the school level, other tobacco policies and factors may reduce tolerance of smoking. Such policies ensued from the Framework Convention on Tobacco Control (FCTC), adopted by the World Health Assembly in 2003 in response to the globalization of the tobacco epidemic (World Health Organisation, 2003). Among those policies, smoke-free and tobacco taxation policies, mass media campaigns and health warnings on the harms of tobacco consumption, and greater accessibility to smoking cessation were found to be the most effective in reducing smoking (Hoffman & Tan, 2015). Tobacco control policies aim to denormalize smoking by creating an environment in which smoking is less desirable, accessible, and socially acceptable (Bayer & Bachynski, 2013; California Department of Health Services, 1998). An environment in which smoking is denormalized, and adolescents who smoke are more and more socially marginalized, as others found with adults (Christakis & Fowler, 2008) might therefore explain the decrease in the diffusion centrality of smoking over time.

This paper did not aim to quantify the social multiplier effect generated by a policy intervention, as a few studies have done in other domains (Bruhin et al., 2020; Gray & Picone, 2018; Konc et al., 2021; Kroft, 2008). It does, however, highlight the need to consider the impact of a policy at a network level rather than solely at an individual level, such as it had previously been done. On the one hand, the analyses of indegree centrality reflect the association between school tobacco policies and the social prestige related to smoking at an individual level: adolescents who had tried smoking at

least once and those who smoked on school premises were less popular when the policies were stronger. On the other hand, the analyses of diffusion centrality captured the centrality and clustering of smoking at a network level. Taking the network level into account is especially useful when looking at a behaviour like smoking, which is known to involve complex contagion (Kim et al., 2015). In their article, DiMaggio and Garip (2012) highlighted three classes of network effects that may occur in behaviour adoption: (1) network externalities, i.e. the behaviour is more valuable if others also adopt it; (2) social learning, i.e. the behaviour is adopted due to the transfer of information or assistance; and (3) normative influence, i.e. the behaviour is adopted due to positive or negative sanctions. They then applied these network effects to the mechanisms of complex contagion identified by Centola and Macy (2007). They suggested that a behaviour is subject to complex contagion if it is risky and complex to adopt, not easily observable, perceived as illegitimate, and requires peer support to be sustained (DiMaggio & Garip, 2012). By providing a school environment that is less permissive of smoking, school tobacco policies may have an impact on those network effects and therefore on the complexity of the behaviour contagion. They may reduce network externalities as they make it less valuable and more risky for an adolescent to adopt the behaviour. They may reduce social learning by making smoking less visible. Finally, they may reduce normative influence as smoking is not framed positively. All in all, such policies would gain from being evaluated at a network level on top of the more common, individual level.

This study and the diffusion centrality measure, however, have their limitations. First, our name generator informed us of relational states rather than relational events (Borgatti & Halgin, 2011) as adolescents were asked to name their best friends. To accurately measure the diffusion centrality of smoking, we could have asked adolescents to cite the friends whose values they share, the friends they think influence them, or the friends they spend their school breaks with. Moreover, we did not take into account the strength of the ties (Centola & Macy, 2007) or the differences in strength between interpersonal influence processes. Indeed, such differences could lead to further differences in the diffusion of a behaviour, even if two networks were similar in terms of relationships and behaviours (Gest et al., 2011). Second, the name generator only included five alters, so we may have missed some ties in the network. Such name generators are, however, often used in the literature. Third, adolescents who have more out-of-school friendships are more likely to smoke (Ennett et al., 2006). Outside of school activities, such unsupervised friendships may indeed promote smoking (Ennett et al., 2008). We do not have much information, however, on out-of-school friendships, which prevents us from taking their potential influence into account (Witkow & Fuligni, 2010). Finally, due to the cross-sectional study design, we cannot conclude on the causality nor the direction of potential causal associations between school tobacco policies and the diffusion centrality of smoking. Further research should be carried out with an experimental design to ascertain this effect.

Despite the limitations outlined above, this study has many strengths. It offers new insights into the impact of a policy on the diffusion of a behaviour, specifically on the association between school tobacco policies and the diffusion centrality of smoking and of smoking on school premises. It is also the first study to apply the concept of diffusion centrality to research on adolescent health, with an international and longitudinal social network survey. A measure of this kind, which captures the diffusion potential of adolescents who smoke, through their popularity and their friends' popularity, offering a combination of local and global centrality, might be a good way to approach smoking, a behaviour where peer influences are key. Moreover, rather than solely looking at the relationship between a policy and a behaviour at an individual level, this study captures the social payoff of this behaviour in a network. To a certain extent, it also contributes to the literature on the social multiplier effect. In view of all that has been mentioned so far, this measure seems relevant to consider in further research on the topic.

Conclusion

This study shows that, overall, the diffusion centrality of smoking has decreased over time. Moreover, stronger school tobacco policies were associated with lower diffusion centrality of smoking among adolescents. Diffusion centrality may be an appropriate measure for capturing the impact of a policy on a network, especially when looking at a behaviour for which social interactions and influences are key. It could also be valuable to evaluate the diffusion centrality of not smoking or of negative attitudes towards smoking. We believe that this study can offer insights in the development of interventions based on network structure and that further applications of the concept of diffusion centrality could serve to recruit key players for peer-interventions. This is in line with the conclusion reached by Drago et al. (2020) that one should target the nodes who have the highest diffusion centrality to optimize an intervention's social multiplier effect. Another way to use this concept is in the evaluation of school tobacco policies. The effectiveness of such policies could be measured with a particular focus on the adolescents who are the most diffusive in the network, assuming that if they are impacted by a policy, those around them will be too.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11121-022-01486-x.

Acknowledgements We would like to thank all school staff members and students who participated in the study. We would like to acknowledge our colleagues who took part in the collection of the SILNE WP5 data: Jaana Kinnunen, Geatano Roscillo, Pierre-Olivier Robert, and Joanna Alves, as well as the SILNE-R WP8 data: Pauline A.W. Nuyts, Michael Schreuders, Diego Marandola, Teresa Leão, Pierre-Olivier Robert, Adeline Grard, Jaana Kinnunen, Laura Hoffmann, and Martin Mlinaric. We would like to acknowledge the work done by Mostafa Berdii and Adeline Grard on the data management. We would like to thank Alain Guillet and the SMCS-UCLouvain team for their precious assistance with statistics and Laura Jones for the English editing.

Author Contribution Nora Mélard: Conceptualization, Methodology, Formal analysis, Data curation, Writing – Original Draft, Writing – Review and Edition. Adeline Grard: Conceptualization, Writing – Review and Edition. Jean-Charles Delvenne: Methodology, Resources, Writing – Review and Edition. Liesbeth Mercken: Methodology, Resources, Writing – Review and Edition. Julian Perelman: Writing – Review and Edition, Project administration, Funding acquisition. Anton E. Kunst: Writing – Review and Edition, Project administration, Funding acquisition. Vincent Lorant: Conceptualization, Methodology, Resources, Writing – Review and Edition, Supervision, Project administration, Funding acquisition.

Funding This study is part of the SILNE-R project "Enhancing the effectiveness of programmes and strategies to prevent smoking by adolescents: a realist evaluation comparing seven European countries", which was supported by the European Union's Horizon 2020 research and innovation programme under the SILNE-R Grant Agreement number 635056. The Belgian team was also supported by a grant from the FNRS: Crédit de Recherche n°23593456.

Declarations

Ethical Approval *Belgium* 2013: Commission d'Ethique Biomédicale, reference number: 2012/09OCT/461. 2016: Comité d'éthique Hospitalo-Facultaire des Cliniques Universitaires Saint-Luc, reference number: 2012/09OCT/461. N° enregistrement belge B403201215182. *Germany* 2013: Ethics committee, Medical Faculty, Martin-Luther-University Halle-Wittenberg, Germany, reference number: 2012–112, approved on 13/12/2012. 2016: Ethical approval MLU Halle-Wittenberg: 2016–90 hm-bü. Supervisory school authority Han(n)over: H 1 R b—81402—55—2016. Supervisory school authority Lüneburg (Celle): LG 1 R.22 – 503000. *Portugal* 2013: General Directorate for Education (Direção Geral da Educação), reference number: 0338600001, approved on 02/11/2012. 2016: General Directorate for education, reference number 0338600002, approved on 26/06/2016. *The Netherlands* 2013: Medical Ethical Committee of the AMC, reference number: W12_256#12.17.0290. 2016: The Medical Ethics Review Committee of the Academic Medical Center confirmed that the Medical Research Involving Human Subjects Act (WMO) does not apply to the SILNE-R study and that official approval was therefore not required: reference number W16_252 # 16.297, 11 August 2016. *Finland* 2013: Ethics Committee of the Tampere region. Favourable Statement reference number: 10/2012. 2016: Ethics Committee of the Tampere Region, Statement 29/2016. *Italy* 2013: Ethics committee, Azienda Unità Sanitaria, Locale Frosinone, Italy, reference number: 862, approved on 13/11/2012. 2016: Ethical Committee "Lazio 2", protocol number 0068451/2016.

Informed Consent Informed consent was obtained from all individual participants included in the study.

Conflict of Interest The authors declare no competing interests.

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