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Dental Caries Clusters among Adolescents in England, Wales, and Northern Ireland in 2013: Implications for Proportionate Universalism

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Keywords
Children's Dental Health Survey 2013 · Dental caries · Pattern · Hierarchical clustering analysis · Risk factors

Abstract
Management of dental caries in adolescents presents a population health challenge; thus, it is important to use national epidemiological data to inform policy and action to improve oral health and address inequalities. The aims of this research were to examine dental caries clusters among 15-year-olds, taking account of caries thresholds, and explore associated factors to inform public health action. Secondary analysis of the oral health data on 2,160 15-year-olds from the 2013 Children's Dental Health Survey in England, Wales, and Northern Ireland was performed. Hierarchical cluster analysis of dental caries experience was conducted across all surfaces and at 4 decay diagnostic thresholds (*clinical*: International Caries Detection and Assessment System [ICDAS] 1–6, *cavitated*: ICDAS 3–6, *obvious*: ICDAS 4–6, and *extensive obvious*: ICDAS 5–6 *decay*). Ordered logistic regression was used to estimate the association of behavioural and psychosocial factors with the clusters generated in relation to both *clinical* and *obvious decay* experience which are of clinical and epidemiological relevance. A 4-cluster decay pattern representing "low" to "extremely high" decay experience was observed under each of the dental caries diagnostic criteria. For *clinical decay*, which includes visual enamel caries, 28.70% had low, 39.77% medium, 26.71% high, and 4.81% extremely high caries status. In the adjusted model, significant risk factors for *clinical decay* included non-modifiable (sex, region, school type, and area deprivation) and modifiable (higher sugar intake at 4 or more times per day and suboptimal dental attendance) factors. This study suggests 4 distinct dental caries patterns among adolescent children nationally. Dental caries clusters demonstrate the importance of embracing proportionate universalism in addressing dental caries in the population oral health strategy.

Introduction

Dental caries, one of the most prevalent chronic diseases in children and adults, represents a major public health challenge globally and nationally [Pitts et al., 2017; GBD 2019 Diseases and Injuries Collaborators, 2020]. It is a progressive, conceptually "staged" and complex dis-

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ease, which involves interactions between the tooth structure, oral microbial biofilm, and dietary carbohydrates [Pitts and Zero, 2016], influenced by host factors. The initiation and progression of dental caries are influenced by a range of factors including genetic, demographic, behavioural factors, psychological, and socioeconomic factors [Zero, 1999; Thomson et al., 2009; Hara and Zero, 2010; Shaffer et al., 2013b; Pitts and Zero, 2016], only some of which are modifiable.

Groups with similar caries patterns might represent differences in risk factors or susceptibility to decay. In order to evaluate potential effects of intervening on specific categories of population/teeth/surface [Ismail et al., 2018], Vernazza et al. [2016] have considered subgroups of adults with varying caries risk probability. Previous research suggests that utilizing hierarchical clustering analysis may facilitate grouping tooth surfaces according to the presence of different types of caries lesions such as pits and fissures molar surfaces and smooth surfaces by the type of tooth in the upper and lower maxillae [Shaffer et al., 2012; Shaffer et al., 2013a, b]. Cluster analysis is a statistical technique that groups similar items into groups (termed clusters), based only upon their scores on observed variables [Galluccio et al., 2013; Hofstetter et al., 2014]. Dental caries experience and its associated risk factors are more likely to be homogeneous within clusters than between them [Masood et al., 2015]. The degree of caries risk is more comparable for different teeth or surfaces within the same individual than among individuals [Hannigan and Lynch, 2013]. Much of the analysis of dental caries data to date has focused on population averages and risk factors rather than looking at the clustering within populations.

Adolescence is a phase of life in which "the opportunities for health are great and future patterns of adult health are established" [Sawyer et al., 2012]. Defined by the World Health Organization as the second decade of life (10–19 years) [WHO, 2017], it represents the transition from childhood to adulthood, in which young people at 15 years of age are midway. While there is relatively little dental research on young people on their mid-teens, longitudinal studies suggest the presence of disease clusters [Warren et al., 2017], which have implications or longer term disease trajectories [Hong et al., 2020].

The 2013 Children's Dental Health Survey (CDHS 2013) was commissioned by the Health and Social Care Information Centre of the United Kingdom (UK). In the previous 4 surveys, *obvious decay* (International Caries Detection and Assessment System [ICDAS] 4–6, non-cavitation lesions into dentine and above) was considered as the dental caries threshold, which was consistent with the WHO oral health surveys basic methods [WHO, 2013]. In line with caries management shifting from a restoratively orientated to a minimally interventive approach, supported by early diagnosis [FDI WDF, 2016], *clinical decay* (ICDAS 1–6, non-cavitated enamel caries and above) includes enamel lesions and represents the criteria used by clinicians, which was recognized as diagnostic threshold for the first time in this series of national surveys within the UK. Initial analysis of these findings suggests that measurement thresholds for caries matter, as just 46% 15-year-old had *obvious decay* experience, while 63% had *clinical decay* [Pitts et al., 2015; Wang et al., 2021]. Furthermore, 15-year-olds exhibited higher disease prevalence than their counterparts at 12 years of age [Pitts et al., 2015; Vernazza et al., 2016; Wang et al., 2021], which was a necessary consequence of the permanent dentition being exposed to the oral environment for a prolonged period, ranging from 3 to 9 years (depending on the tooth) among 15-year-olds.

Socioeconomic inequalities in dental caries are well documented [Schwendicke et al., 2015]. Upstream strategies to prevent dental caries should be based on the principle of proportionate universalism, by combining whole population strategies (such as sugar tax or water fluoridation) with targeted interventions for those with the greatest need [Marmot, 2010]. Understanding the patterns of presentation of dental caries in a population becomes crucial for policy makers and public health specialists to inform tailored interventions for specific subgroups [Kassebaum et al., 2017]. The aim of this study was therefore to examine dental caries clusters by dental caries threshold among 15-year-old pupils in England, Wales, and Northern Ireland using data from the latest national survey and to explore associated risk factors.

Materials and Methods

Data Source

Data were available for analysis from the CDHS 2013, the methodological details of which are available online [Anderson et al., 2015]. In total, a representative sample of eligible 15-years-olds (n = 2,418) attending secondary schools in England, Wales, and Northern Ireland was examined [Pitts et al., 2015]. In line with ICDAS, a visual change in enamel was recorded. Caries assessment was undertaken by the surface by visual oral examination using a plane mouth mirror and ball-ended CPITN or WHO probes after drying with cotton wool/gauze. No X-ray examinations were undertaken. For this study, the CDHS codes have been adapted into the corresponding ICDAS format for clarity, as shown in Figure 1 [Pitts et al., 2017]: "sound" (including any subclinical decay), vi-

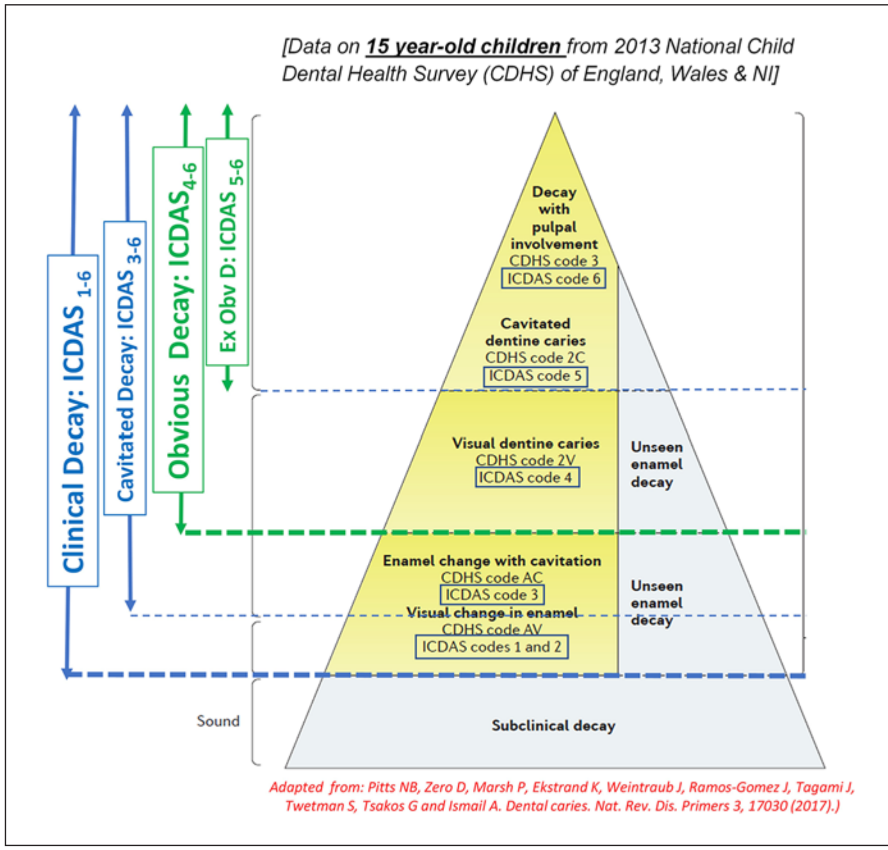

Fig. 1. Mapping the codes and thresholds used in the CDHS 2013 survey with ICDAS thresholds. ICDAS, International Caries Detection and Assessment System; CDHS, Children's Dental Health Survey.

sual change in enamel (ICDAS 1* & 2), visual enamel change with cavitation (ICDAS 3), visual dentine caries (non-cavitated; ICDAS 4), cavitated dentine caries (ICDAS 5), and decay with pulpal involvement (ICDAS 6). In addition, filled with recurrent decay (with/without cavitation), filling needs replacement, sound fillings (F), and extracted due to caries (M) were also recorded [Anderson et al., 2015; Pitts et al., 2015]. Dental caries activity was not assessed. The original survey received ethical approval from University College London Ethics Committee (Project ID: 2000/003).

In order to examine if the caries pattern was stable under different diagnostic thresholds, cluster analysis was undertaken for 15-year-olds with complete caries data relating to their permanent dentition. Caries status was assessed at 4 thresholds:

- "*clinical decay*" (ICDAS 1–6): $D_{1\text{-}6}$MFS,
- "*cavitated decay*" (ICDAS 3–6): $D_{3\text{-}6}$MFS,
- "*obvious decay*" (ICDAS 4–6): $D_{4\text{-}6}$MFS, and
- "*extensive obvious decay*" (ICDAS 5–6): $D_{5\text{-}6}$MFS.

To model the patterns of caries occurrence among population, each tooth surface was re-coded as "0" for "sound" or missing due to reasons other than decay, and "1" for decayed, filled, or missing due to decay, under each of the above diagnostic thresholds. Three self-reported dental behavioural factors and 1 psychological factor were collected through pupil questionnaires, together with sociodemographic data: toothbrushing frequency (twice a day or more/once a day or less); frequency of sugar intake (4 or more times a day/<4 times a day) – aggregating daily consumption of sweets, biscuits, cakes, fruits, soft drinks that contain sugar, energy/sports drinks, and fruit juice or smoothies; and pattern of usual dental attendance (regular or irregular/none) were all used as binary categorical variables. Self-rated dental anxiety was evaluated by the Modified Dental Anxiety Scale (MDAS), based on responses to 5 questions, and recategorized into 3 groups: low/no anxiety (scores 5–9), moderate anxiety (scores 10–18), and extreme anxiety (scores 19–25). Certain sociodemographic factors were also involved as potential confounders [Kassebaum et al., 2015; Ravaghi et al., 2016], including sex (male/female), ethnicity (white/non-white), Government Office Region (11-category), school type (independent/secondary/academy or free school), free school meal eligibility, and index of multiple deprivation quintile [NISRA, 2010; Welsh Government, 2011; MHCLG, 2011]. The last 2 variables were generally considered as indicators of family socioeconomic status.

Statistical Analysis

Hierarchical cluster analysis measures the distances between individual observations, successively grouping similar individuals into clusters, small into bigger clusters, to ultimately a cluster hierarchy [Ward, 1963]. To identify whether a hierarchy create for caries susceptibility exists, and generate groups of similar caries affected status in individuals among 128 tooth surfaces under different caries diagnostic criteria, Ward's minimum variance method, a type of agglomerative hierarchical clustering, was used in this research [Ward, 1963; Shaffer et al., 2013b]. For each participant, the caries status of all 128 surfaces across 28 permanent teeth (4

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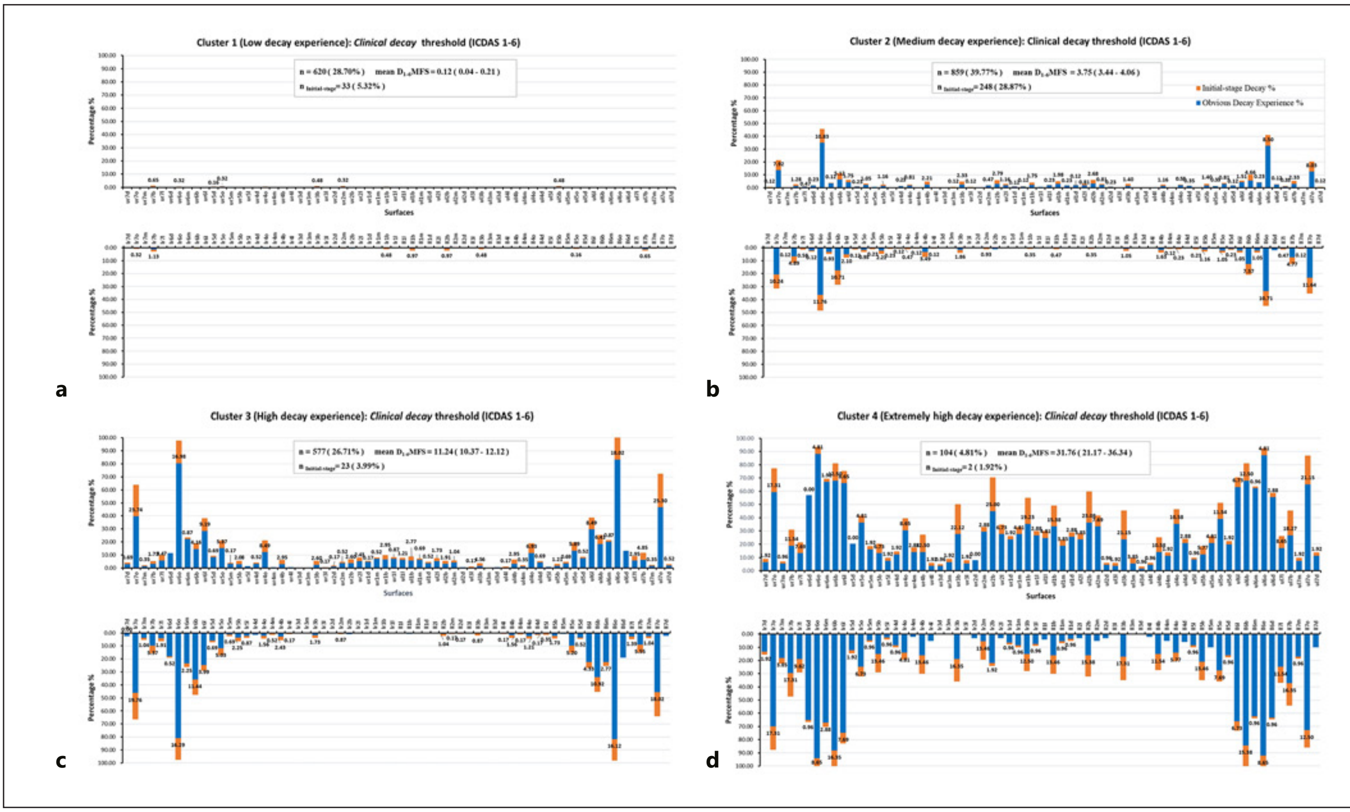


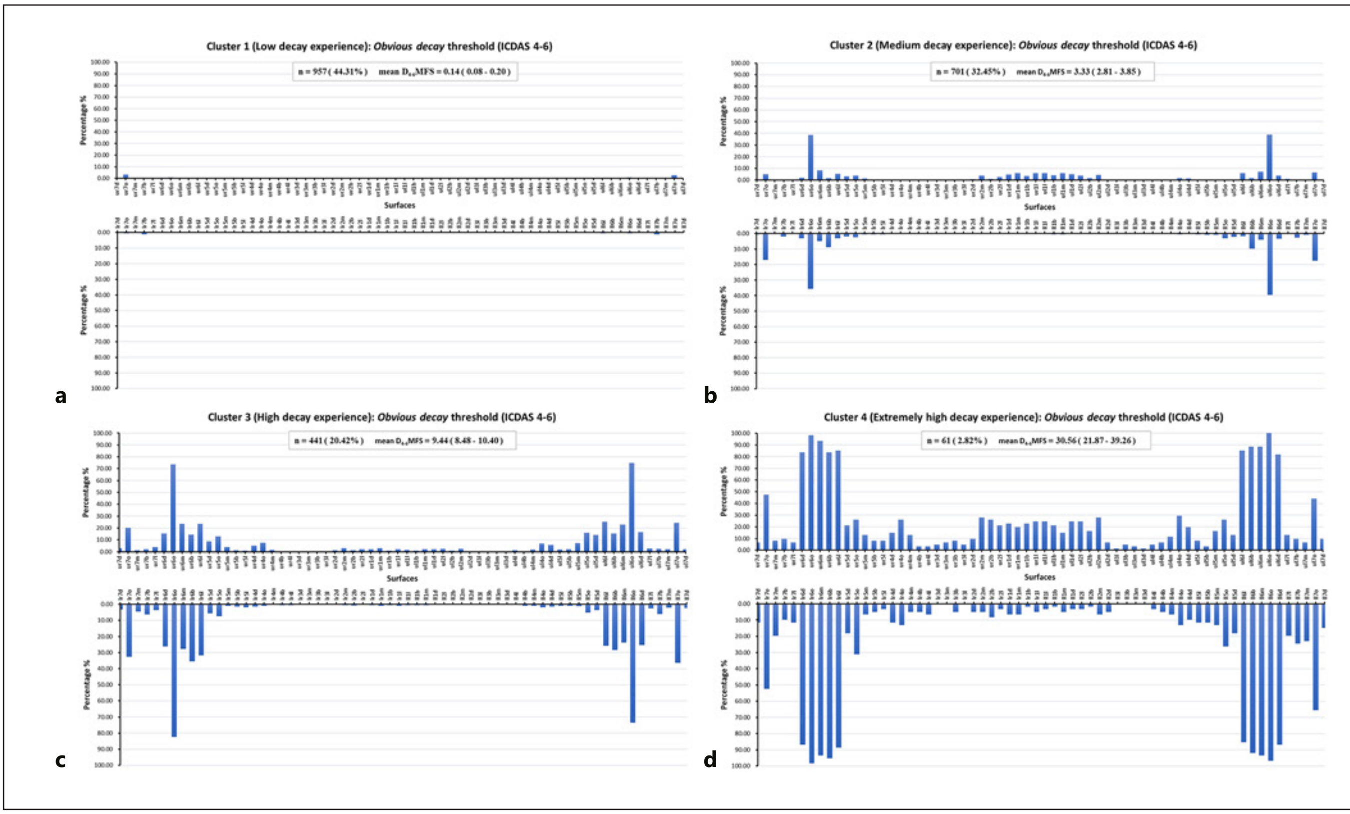
Fig. 2. Patterns of *clinical decay* experience (ICDAS 1–6) by the surface among 15-year-olds in England, Wales, and Northern Ireland, 2013 (n = 2,160). Note: Figure **a–d** represents Cluster 1–4, respectively. *Clinical decay* experience (ICDAS 1–6) includes dental caries in enamel (ICDAS 1–3) represented by orange and *obvious decay* experience (ICDAS 4–6) is represented in blue. ICDAS, International Caries Detection and Assessment System.

surfaces per incisor or canine; 5 surfaces per premolar or molar, excluding third molars) was considered as 128 variables. Then, the square Euclidean distance was used to determine the similarity of caries-affected probability of each tooth surface among clusters, to identify involved samples into several groups according to their caries patterns. Next, we applied cluster-analysis stopping rules to determine the number of clusters. A large value for the *Caliński-Harabasz pseudo-F* index, a large *Duda-Hart Je(2)/Je(1)* index value, and a small *Duda-Hart pseudo-T*-squared value were used to indicate distinct clustering [Everitt et al., 2011].

Complex survey design (stratification and clustering) was taken into account [Shaffer et al., 2013b]. To evaluate the ability of discriminating individuals from different patterns of caries status by clustering, mean DMFS and composition of tooth surfaces affected by different stages of caries among clusters in accordance with 4 diagnostic thresholds were calculated and then further compared by the one-way *ANOVA* or the *Kruskal-Wallis* test. The proportions of cases aggregated at cluster, according to *clinical* or *obvious* diagnostic thresholds, were further evaluated to explore the compatible decay diagnostic threshold for clustering which could meet the requirements from clinical and epidemiological perspectives, respectively.

As the cluster level of *clinical decay* and *obvious decay* experience was an ordinal categorical outcome, ordered logistic regression (OL regression) was used to estimate the association of behavioural and psychological factors with clusters using the similar 2-stage modelling strategy with weightings applied. Unadjusted and adjusted models were successively built as followed. First, the association of toothbrushing frequency, frequency of sugar intake, usual pattern of dental attendance, and MDAS grouping with clusters were estimated; then, potential confounders representing demographic status were introduced into the model to make an adjusted estimation. Model fitness was assessed by a user-written program gologit2 *Wald* test to confirm that our fully adjusted OL regression model did not violate the proportional odds assumption [Williams, 2016]. Odds ratios (ORs), 95% confidence intervals (95% CI), and level of significance were reported and compared in all models.

The distribution of excluded pupils was compared with research samples in relevant variables by using a χ^2 test to evaluate the impact of missing data. All analyses were conducted by Stata/SE 15 (StataCorp LLC, College Station, TX, USA). $p < 0.05$ was considered statistically significant.



Color version available online

Fig. 3. Patterns of *obvious decay* experience (ICDAS 4–6) by the surface among 15-year-olds in England, Wales, and Northern Ireland, 2013 (n = 2,160). Figure **a–d** represents Cluster 1–4, respectively. ICDAS, International Caries Detection and Assessment System.

Results

Data on 2,160 15-year-olds with 128 tooth surfaces were involved in hierarchical clustering analysis, representing 89.3% of the pupils who took part in dental examinations. Adolescents excluded from this analysis because of missing information on caries data were more likely to be from Wales and less likely to be from Northern Ireland; otherwise, no other difference was found between the research sample and those excluded.

We identified 4 clusters of adolescents according to the 4 diagnostic decay thresholds examined (*clinical/cavitated/obvious/extensive obvious decay*) as presented in Figures 2 and 3 and online suppl. Figures 1 and 2; see www.karger.com/doi/10.1159/000518964 for all online suppl. material. The 4 clusters reflect: (1) “low,” (2) “medium,” (3) “high,” and (4) “extremely high” decay experience, respectively. Figures 2 and 3 present the findings in relation to *clinical decay* and *obvious decay* thresholds by the surface. Figure 2 presents the level of caries in enamel in orange, with *obvious decay* experience in blue. The orange component, therefore, demonstrates the caries that would be “missed” if the diagnostic threshold for caries is merely *obvious decay* (Fig. 3). Comparing the proportions of adolescents in each level across Figures 2 and 3 provides important insights. Whereas 44.3% would appear low caries risk if the threshold is *obvious decay*, when *clinical decay* is considered, this reduces to 28.7%. The higher risk status of some 15.6% of children would be “missed.” And at the other extreme, it rises from 2.82% to 4.81%.

The other 2 thresholds examined (*cavitated* and *extensive obvious decay*) are presented in the online suppl. Figures 1 and 2 to provide a full overview of the findings. Clear patterns of caries distribution across the 4 thresholds were evident in relation to surfaces representing pits, fissures, and smooth surfaces (shown in Fig. 2, 3, online suppl. Fig. 1, 2).

In relation to *clinical decay* (Fig. 2), Cluster 1 representing low caries experience showed that caries was mainly evident on occlusal and buccal surfaces of molars

Table 1. Comparison of cases in 4 level of dental experience clusters between *clinical* (ICDAS 1–6) and *obvious* (ICDAS 4–6) *decay* thresholds

	Clusters according to *clinical decay* threshold (ICDAS 1–6)				
	Cluster 1 (low DE)	Cluster 2 (medium DE)	Cluster 3 (high DE)	Cluster 4 (extremely high DE)	total
Clusters according to *obvious decay* threshold (ICDAS 4–6)					
Cluster 1 (low DE)					
N	617	300	38	2	957
Obvious, %	64.47	31.35	3.97	0.21	100.00
Clinical, %	99.52	34.92	6.59	1.92	44.31
Cluster 2 (medium DE)					
N	2	479	204	16	701
Obvious, %	0.29	68.33	29.10	2.28	100.00
Clinical, %	0.32	55.76	35.36	15.38	32.45
Cluster 3 (high DE)					
N	1	80	333	27	441
Obvious, %	0.23	18.14	75.51	6.12	100.00
Clinical, %	0.16	9.32	57.71	25.96	20.42
Cluster 4 (extremely high DE)					
N	0	0	2	59	61
Obvious, %	0.00	0.00	3.28	96.72	100.00
Clinical, %	0.00	0.00	0.34	56.74	2.82
Total					
N	620	859	577	104	2,160
Obvious,%	28.70	39.77	26.71	4.81	100.00

Obvious %, proportion in cluster generated according to *obvious decay* threshold (ICDAS 4–6); Clinical %, proportion in cluster generated according to *clinical decay* threshold (ICDAS 1–6); Low DE, low decay experience; medium DE, medium decay experience; high DE, high decay experience; extremely high DE, extremely high decay experience; ICDAS, International Caries Detection and Assessment System.

with extremely low prevalence. Cluster 2 (medium) aggregated individuals with a higher proportion of carious occlusal surfaces in molars, with a range of other surfaces involved. In Cluster 3, dental caries was present on similar surfaces to Cluster 2, but more frequently and with premolars increasingly involved. Adolescents in Cluster 4 had lesions in almost all teeth, whereby even a certain percentage of mandibular anterior teeth were affected. Over 80% surfaces of their first permanent molars had evidence of *clinical* dental caries.

The similarities and differences of cases aggregated into the same levels of decay experience generated under those 2 thresholds are further summarized in Table 1. Although under different decay diagnostic thresholds, average dental caries experience levels (DMFS) for adolescents ranged from 0.12 to 0.25 in Cluster 1, to 28.86–31.76 in Cluster 4 (shown in Fig. 2, 3, online suppl. Fig. 1, 2), whereby children in the very highest cluster had a lot of *obvious/clinical decay*. Interestingly, 35% of cases identified in Cluster 1 for *obvious decay* threshold were grouped at higher level clusters when the earlier threshold of dental caries was considered (shown in Table 1). The characteristics of every cluster could be distinguished from each other among 4 thresholds by comparing the distribution of each ICDAS code (shown in online suppl. Table 1). Of the 4 thresholds examined, 2 representative diagnostic criteria were chosen to be involved in the subsequent analysis: *clinical decay* experience, representing the criteria used now for examining and providing care by clinicians, and *obvious decay* experience relating to traditional epidemiological surveys.

As dental caries clusters are a novel measure, representing the level of dental caries experience, its associated demographic, socioeconomic, psychosocial, and behavioural factors were further explored at both key thresholds. In total, 1,789 (74.0%) 15-year-old pupils with com-

Table 2. Characteristics of 15-year-olds by dental caries experience clusters in England, Wales, and Northern Ireland, 2013 (n = 1,789)

Variables	*N*	Weighted % (95% CI)	Clusters according to *clinical decay* threshold (ICDAS 1–6)					Clusters according to *obvious decay* threshold (ICDAS 4–6)				
			mean D_{1-6}MFS (95% CI)	LL cluster *n* (%)	ML cluster *n* (%)	HL cluster *n* (%)	EHL cluster *n* (%)	mean D_{4-6}MFS (95% CI)	LL cluster *n* (%)	ML cluster *n* (%)	HL cluster *n* (%)	EHL cluster *n* (%)
Sex												
Male	853	48.99 (42.77, 55.24)	4.37(3.49, 5.25)	282 (33.06)	324 (37.98)	216 (25.32)	31 (3.63)	2.55 (1.98, 3.12)	408 (47.83)	280 (32.83)	151 (17.70)	14 (1.64)
Female	936	51.01 (44.76, 57.23)	4.41 (3.50, 5.33)	227 (24.25)	387 (41.35)	270 (28.85)	52 (5.56)	2.76 (2.20, 3.12)	385 (41.13)	290 (30.98)	224 (23.93)	37 (3.95)
Free school meal eligibility												
Not eligible	1,403	84.86 (80.26, 88.54)	4.07 (3.23, 4.90)	438 (31.22)	553 (39.42)	361 (25.73)	51 (3.64)	2.32 (1.89, 2.76)	670 (47.75)	436 (31.08)	268 (19.10)	29 (2.07)
Eligible	386	15.14 (11.46, 19.74)	6.22 (4.86, 7.58)	71 (18.39)	158 (40.93)	125 (32.38)	32 (8.29)	4.51 (3.55, 5.48)	123 (31.87)	134 (34.72)	10 (27.72)	22 (5.70)
Region												
London	114	9.35 (6.51, 13.26)	3.56 (2.51, 4.60)	40 (35.09)	52 (45.61)	21 (18.42)	1 (0.88)	2.63 (1.88, 3.38)	60 (52.63)	32 (28.07)	21 (18.42)	1 (0.88)
South East	101	17.20 (7.87, 33.56)	2.59 (1.47, 3.71)	51 (50.50)	26 (25.74)	21 (20.79)	3 (2.97)	2.59 (1.03, 2.58)	59 (58.42)	30 (29.70)	12 (11.88)	0 (0)
West Midlands	110	10.73 (8.20, 13.92)	3.73 (2.54, 4.92)	45 (40.91)	52 (47.27)	11 (10.00)	2 (1.82)	2.95 (1.63, 4.28)	74 (67.27)	27 (24.55)	7 (6.36)	2 (1.82)
East of England	96	11.48 (5.56, 22.22)	2.63 (0.43, 4.83)	48 (50.00)	31 (32.29)	16 (16.67)	1 (1.04)	1.32 (0.22, 2.42)	67 (69.79)	22 (22.92)	7 (7.29)	0 (0)
East Midlands	76	7.11 (1.76, 24.68)	5.60 (3.70, 7.51)	14 (18.42)	32 (42.11)	26 (34.21)	4 (5.25)	2.06 (1.23, 2.90)	60 (54.05)	37 (33.33)	14 (12.61)	0 (0)
Yorkshire and the Humber	111	10.77 (5.53, 19.91)	4.42 (1.94, 6.90)	37 (33.33)	51 (45.95)	22 (19.82)	1 (0.90)	3.90 (1.99, 5.81)	62 (44.29)	41 (29.29)	35 (25.00)	2 (1.43)
Wales	393	5.33 (3.40, 8.28)	5.92 (4.49, 7.35)	91 (23.16)	184 (46.82)	103 (26.21)	15 (3.82)	3.76 (2.59, 4.94)	160 (40.71)	154 (39.19)	69 (17.56)	10 (2.54)
South West	80	7.80 (4.42, 13.38)	4.49 (0.50, 8.84)	27 (33.75)	30 (37.50)	20 (25.00)	3 (3.75)	2.28 (0.62, 3.95)	47 (58.75)	16 (20.00)	15 (18.75)	2 (2.50)
North West	171	12.14 (6.23, 22.32)	6.89 (5.12, 8.66)	37 (21.64)	51 (29.82)	69 (40.35)	14 (8.19)	3.44 (2.40, 4.48)	64 (37.43)	54 (31.58)	47 (27.49)	6 (3.51)
North East	140	4.58 (2.23, 9.17)	5.21 (2.66, 7.76)	41 (29.29)	52 (37.14)	42 (30.00)	5 (3.57)	2.78 (1.08, 4.49)	32 (42.11)	23 (30.26)	19 (25.00)	2 (2.63)
Northern Ireland	397	3.52 (2.62, 4.71)	8.42 (6.71, 10.13)	78 (19.65)	150 (37.78)	135 (34.01)	34 (8.56)	6.73 (5.48, 7.97)	108 (27.20)	134 (33.75)	129 (32.49)	26 (6.55)
School type												
Independent school	77	8.20 (2.27, 25.55)	1.59 (0.28, 2.90)	38 (49.35)	39 (50.65)	0 (0)	0 (0)	0.82 (0.59, 1.04)	55 (71.43)	21 (27.27)	1 (1.30)	0 (0)
Academy or free school	385	39.27 (26.62, 53.55)	4.05 (2.73, 5.38)	156 (40.52)	131 (34.03)	88 (22.86)	10 (2.60)	2.32 (1.58, 3.07)	225 (58.44)	95 (24.68)	60 (15.58)	5 (1.30)
Secondary school	1,327	52.53 (36.10, 68.43)	5.08 (4.20, 5.96)	315 (23.74)	541 (40.77)	398 (29.99)	73 (5.50)	3.19 (2.62, 3.77)	513 (38.66)	454 (34.21)	314 (23.66)	46 (3.47)
Index of multiple deprivation quintile												
80–100% least deprived	202	15.54 (10.20, 22.97)	3.13 (1.76, 4.49)	88 (43.56)	77 (38.12)	34 (16.83)	3 (1.49)	1.65 (0.84, 2.47)	120 (59.41)	49 (24.26)	32 (15.84)	15 (0.50)
60–80%	275	19.32 (13.42, 27.01)	4.09 (2.16, 6.03)	104 (37.82)	106 (38.55)	54 (19.64)	11 (4.00)	1.98 (1.11, 2.85)	152 (55.27)	80 (29.09)	38 (13.82)	5 (1.82)
40–60%	290	18.48 (13.11, 25.40)	3.86 (2.72, 4.99)	82 (28.28)	133 (45.86)	70 (24.14)	5 (1.72)	2.34 (1.56, 3.12)	123 (42.41)	103 (35.52)	61 (21.03)	3 (1.03)
20–40%	382	18.17 (13.75, 23.62)	4.55 (3.68, 5.42)	98 (25.65)	155 (40.58)	113 (29.58)	16 (4.19)	3.12 (2.52, 3.71)	165 (43.19)	123 (32.20)	83 (21.73)	11 (2.88)
0–20% most deprived	640	28.49 (19.95, 38.91)	5.53 (4.32, 6.74)	137 (21.41)	240 (37.50)	215 (33.59)	48 (7.50)	3.58 (2.43, 4.73)	233 (36.41)	215 (33.59)	161 (25.16)	31 (4.84)
Ethnicity												
White	1,488	80.83 (74.96, 85.59)	4.48 (3.47, 5.48)	405 (27.22)	600 (40.32)	409 (27.49)	74 (4.97)	2.66 (2.08, 3.23)	638 (42.88)	480 (32.26)	325 (21.84)	45 (3.02)
Non-white	301	19.17 (14.41, 25.05)	4.03 (3.13, 4.92)	104 (34.55)	111 (36.88)	77 (25.88)	9 (2.99)	2.66 (1.79, 3.54)	155 (51.50)	90 (29.90)	50 (16.61)	6 (1.99)
Frequency of brushing teeth												
Twice a day or more	1,412	81.08 (78.53, 83.38)	4.15 (3.34, 4.95)	425 (30.10)	552 (39.09)	376 (26.63)	59 (4.18)	2.47 (2.02, 2.92)	642 (45.47)	443 (31.37)	289 (20.47)	38 (2.69)
Once a day or less	377	18.92 (16.62, 21.47)	5.44 (4.12, 6.75)	84 (22.28)	159 (42.18)	110 (29.18)	24 (6.37)	3.44 (2.28, 4.60)	151 (40.05)	127 (33.69)	86 (22.81)	13 (3.45)
Frequency of sugar intake												
<4 times a day	623	37.89 (34.20, 41.72)	3.24 (2.29, 4.29)	197 (31.62)	260 (41.73)	154 (24.72)	12 (1.93)	1.82 (1.38, 2.27)	300 (48.15)	197 (31.62)	116 (18.62)	10 (1.61)
4 or more times a day	1,166	62.11 (58.28, 65.80)	5.09 (4.25, 5.94)	312 (26.76)	451 (38.68)	332 (28.47)	71 (6.09)	3.16 (2.61, 3.71)	493 (42.28)	373 (31.99)	259 (22.21)	41 (3.52)

Table 2 (continued)

Variables	N	Weighted % (95% CI)	Clusters according to *clinical decay* threshold (ICDAS 1–6): mean $D_{1–6}MFS$ (95% CI)	LL cluster n (%)	ML cluster n (%)	HL cluster n (%)	EHL cluster n (%)	Clusters according to *obvious decay* threshold (ICDAS 4–6): mean $D_{4–6}MFS$ (95% CI)	LL cluster n (%)	ML cluster n (%)	HL cluster n (%)	EHL cluster n (%)
Usual dental attendance												
Regular	1,498	84.69 (80.43, 88.16)	3.82 (3.03, 4.60)	457 (30.51)	612 (40.85)	373 (24.90)	56 (3.74)	2.15 (1.74, 2.56)	698 (46.60)	484 (32.31)	28 (18.89)	33 (2.20)
Irregular/none	291	15.31 (11.84, 19.57)	7.58 (5.85, 9.30)	52 (17.87)	99 (34.02)	113 (38.83)	27 (9.28)	5.45 (4.16, 6.75)	95 (32.65)	86 (29.55)	92 (31.62)	18 (6.19)
Self-rated dental anxiety score MDAS grouping												
Low/no anxiety	643	35.61 (31.67, 39.77)	5.09 (4.08, 6.11)	184 (28.62)	250 (38.88)	188 (29.24)	21 (3.27)	3.13 (2.45, 3.80)	274 (42.61)	250 (38.88)	188 (29.24)	21 (3.27)
Moderate anxiety	923	54.69 (50.07, 59.23)	3.72 (2.87, 4.67)	272 (29.47)	376 (40.74)	235 (25.46)	40 (4.33)	2.11 (1.66, 2.56)	443 (48.00)	273 (29.58)	179 (19.39)	28 (3.03)
Extreme anxiety	223	9.70 (7.67, 12.19)	5.61 (4.09, 7.12)	53 (23.77)	85 (38.12)	63 (28.25)	22 (9.87)	4.04 (2.76, 5.32)	76 (34.08)	78 (34.98)	59 (26.46)	10 (4.48)
Total	1,789	100.00	4.39 (3.60, 5.18)	509 (28.45)	711 (39.74)	486 (27.17)	83 (4.64)	2.66 (2.21, 3.11)	793 (44.33)	570 (31.86)	375 (20.96)	51 (2.85)

CI, confidence intervals; MDAS, Modified Dental Anxiety Scale; ICDAS, International Caries Detection and Assessment System.

plete data on all factors were included. The characteristics and clusters generated by *clinical* and *obvious decay* thresholds are presented in Table 2. Overall, average dental caries experience for *clinical decay* ($D_{1–6}MFS$) was higher at 4.39 (95% CI: 3.60–5.18) than for *obvious decay* ($D_{4–6}MFS$) at 2.66 (95% CI: 2.21–3.11). In terms of demographic factors, females had a greater caries experience, at both thresholds, than boys, but there were no differences between white and non-white groups. In addition, children in Yorkshire and the Humber and North West of England as well as those in Wales and Northern Ireland had a greater caries experience than those in London (shown in Tables 3, 4).

In terms of socioeconomic factors, area deprivation and school type were associated with caries experience at both thresholds, but eligibility for free school meals was not. Children from deprived areas and those in government schools, including academies, had greater odds of having caries experience. In terms of psychosocial factors, moderate dental anxiety was associated with a lower caries experience at both thresholds. Finally, frequent sugar consumption and irregular dental attendance were significantly associated with clusters generated by both thresholds.

The caries experience cluster of an individual can be roughly estimated by the formula generated from the fully adjusted OL regression model according to coefficients and cut-off points. Regardless of diagnostic thresholds, pupils who were in the highest OR categories of all relevant variables had 75–80% predicted proportion to be gathered to high and above level clusters. Children who were in the lowest OR categories of each involved variable had >90% probability of being assigned to Cluster 1 (shown in Table 5).

Discussion/Conclusion

This novel study provides important insight to dental caries experience patterns among young people in mid-adolescence, based on national data, which consider different caries thresholds that are biologically relevant to this prevalent disease. A 4-cluster decay pattern from low to extremely high was identified, taking account of dental caries diagnostic thresholds, with each of the analyses fitting 4 clusters. The association of these ordered clusters with demographic, socioeconomic, psychological, and behavioural factors provides important insights to inform action.

Table 3. Association of dental behaviours, diet, and dental anxiety by *clinical decay* experience (ICDAS 1–6) clusters among 15-year-old teenagers in England, Wales, and Northern Ireland, 2013 (n = 1,789)

Variables	Unadjusted model[a]		Adjusted model[a]	
	coef. (95% CI)	OR (95% CI)	coef. (95% CI)	OR (95% CI)
Sex				
Male	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
Female	0.27 (−0.04, 0.59)	1.32 (0.96, 1.80)	0.42 (0.06, 0.78)*	1.52 (1.06, 2.17)*
Free school meal eligibility				
Not eligible	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
Eligible	0.60 (0.07, 1.12)*	1.81 (1.07, 3.06)*	0.16 (−0.37, 0.69)	1.17 (0.69, 2.00)
Region				
London	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
South East	−0.71 (−1.36, −0.06)	0.49 (0.26, 0.95)*	0.15 (−0.25, 0.54)	1.16 (0.77, 1.72)
West Midlands	−0.20 (−0.76, 0.36)	0.82 (0.47, 1.44)	0.52 (−0.19, 1.23)	1.68 (0.83, 3.41)
East of England	−0.60 (−1.78, 0.57)	0.55 (0.17, 1.77)	0.56 (−0.66, 1.77)	1.74 (0.52, 5.85)
East Midlands	0.12 (−0.72, 0.96)	1.13 (0.49, 2.61)	0.89 (0.03, 1.75)*	2.43 (1.03, 5.75)*
Yorkshire and the Humber	0.31 (−0.44, 1.05)	1.36 (0.65, 2.87)	1.00 (0.36, 1.64)**	2.72 (1.43, 5.15)**
Wales	0.55 (−0.00, 1.11)	1.74 (1.00, 3.03)*	1.02 (0.50, 1.54)***	2.78 (1.65, 4.67)***
South West	−0.08 (−1.81, 1.66)	0.93 (0.16, 5.26)*	1.06 (−0.37, 2.49)	2.88 (0.69, 12.03)
North West	0.64 (−0.00, 1.28)	1.90 (1.00, 3.59)*	1.18 (0.67, 1.69)***	3.27 (1.97, 5.42)***
North East	0.68 (0.19, 1.16)	1.97 (1.21, 3.20)**	1.35 (0.74, 1.97)***	3.87 (2.09, 7.16)***
Northern Ireland	0.91 (−0.38, 1.44)	2.48 (1.46, 4.20)***	1.41 (0.89, 1.93)***	4.09 (2.43, 6.90)***
School type				
Independent school	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
Academy or free school	0.75 (−0.15, 1.65)	2.11 (0.86, 5.19)	0.35 (−0.32, 1.03)	1.42 (0.72, 2.80)
Secondary school	1.19 (0.36, 2.02)**	3.29 (1.44, 7.52)**	0.76 (0.06, 1.46)*	2.14 (1.07, 4.31)*
Index of multiple deprivation quintile				
80–100% least deprived	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
60–80%	0.34 (−0.15, 0.84)	1.41 (0.86, 2.31)	0.39 (−0.15, 0.93)	1.48 (0.86, 2.54)
40–60%	0.52 (−0.00, 1.04)*	1.68 (1.00, 2.83)*	0.63 (0.05, 1.22)*	1.89 (1.05, 3.37)*
20–40%	0.86 (0.35, 1.37)***	2.36 (1.42, 3.92)***	0.79 (0.31, 1.26)***	2.20 (1.37, 13.52)***
0–20% most deprived	1.01 (0.42, 1.59)***	2.74 (1.53, 4.91)***	0.78 (0.29, 1.26)**	2.17 (1.34, 3.54)**
Ethnicity				
White	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
Non-white	−0.01 (−0.49, 0.47)	0.99 (0.62, 1.60)	−0.12 (−0.52, 0.27)	0.88 (0.59, 1.31)
Frequency of brushing teeth				
Twice a day or more	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
Once a day or less	0.34 (0.05, 0.63)*	1.40 (1.05, 1.87)*	0.17 (−0.19, 0.54)	1.19 (0.83, 1.71)
Frequency of sugar intake				
<4 times a day	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
4 or more times a day	0.53 (0.22, 0.83)***	1.70 (1.25, 2.30)***	0.41 (0.07, 0.75)*	1.50 (1.07, 2.11)*
Usual dental attendance				
Regular	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
Irregular/none	0.88 (0.58, 1.17)***	2.41 (1.79, 3.24)***	0.85 (0.46, 1.24)***	2.34 (1.59, 3.45)***
Self-rated dental anxiety score MDAS grouping				
Low/no anxiety	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
Moderate anxiety	−0.19 (−0.40, 0.03)	0.83 (0.67, 1.03)	−0.31 (−0.58, −0.03)*	0.74 (0.56, 0.97)*
Extreme anxiety	0.34 (−0.14, 0.81)	1.40 (0.87, 2.26)	−0.05 (−0.57, 0.46)	0.95 (0.56, 1.59)
/cut1			3.27 (1.72, 4.81)	
/cut2			5.14 (3.58, 6.71)	
/cut3			7.84 (6.09, 9.60)	

OR, odds ratios; CI, confidence intervals; MDAS, Modified Dental Anxiety Scale; ICDAS, International Caries Detection and Assessment System. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$. [a] Unadjusted and full-adjusted ordered logistic regression models were fitted, and OR were reported.

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Table 4. Association of dental behaviours, diet, and dental anxiety by *obvious decay* experience (ICDAS 4–6) clusters among 15-year-old teenagers in England, Wales, and Northern Ireland, 2013 (n = 1,789)

Variables	Unadjusted model[a]		Adjusted model[a]	
	coef. (95% CI)	OR (95% CI)	coef. (95% CI)	OR (95% CI)
Sex				
Male	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
Female	0.19 (–0.09, 0.48)	1.21 (0.91, 1.61)	0.30 (0.00, 0.60)*	1.35 (1.00, 1.83)*
Free school meal eligibility				
Not eligible	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
Eligible	0.54 (0.14, 0.95)**	1.72 (1.14, 2.59)**	0.21 (–0.23, 0.65)	1.23 (0.79, 1.91)
Region				
London	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
South East	–0.51 (–0.99, –0.03)*	0.60 (0.37, 0.97)*	–0.19 (–0.52, 0.35)	0.92 (0.59, 1.42)
West Midlands	–0.60 (–1.10, 0.09)*	0.55 (0.33, 0.91)*	–0.29 (–0.78, 0.21)	0.75 (0.46, 1.23)
East of England	–0.86 (–1.78, 0.06)	0.42 (0.17, 1.06)	–0.34 (–1.25, 0.58)	0.71 (0.29, 1.78)
East Midlands	–0.15 (–0.80, 0.49)	0.86 (0.45, 1.64)	0.34 (–0.35, 1.03)	1.41 (0.71, 2.80)
Yorkshire and the Humber	0.41 (–0.25, 1.05)	1.49 (0.78, 2.86)	0.77 (0.15, 1.39)*	2.17 (1.17, 4.03)*
Wales	0.32 (–0.22, 0.85)	1.37 (0.80, 2.34)	0.59 (0.10, 1.09)*	1.81 (1.10, 2.97)*
South West	–0.33 (–1.46, 0.79)	0.72 (0.23, 2.21)	0.15 (–0.79, 1.08)	1.16 (0.46, 2.96)
North West	0.27 (–0.25, 0.77)	1.31 (0.78, 2.20)	0.49 (0.03, 0.95)*	1.64 (1.04, 2.59)*
North East	0.16 (–0.39, 0.71)	1.17 (0.68, 2.04)	0.38 (–0.21, 0.97)	1.46 (0.81, 2.64)
Northern Ireland	1.05 (0.56, 1.53)***	2.85 (1.75, 4.63)***	1.41 (0.89, 1.93)***	1.35 (0.87, 1.84)***
School type				
Independent school	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
Academy or free school	0.51 (0.08, 0.94)*	1.67 (1.09, 2.56)*	0.45 (0.03, 0.87)*	1.57 (1.04, 2.39)*
Secondary school	0.87 (0.60, 1.14)***	2.39 (1.82, 3.14)***	0.44 (0.04, 0.84)*	1.56 (1.04, 2.32)*
Index of multiple deprivation quintile				
80–100% least deprived	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
60–80%	–0.15 (–0.88, –0.10)	0.87 (0.53, 1.40)	0.18 (–0.17, 0.53)	1.20 (0.84, 1.71)
40–60%	–0.49 (–0.88, –0.10)*	0.61 (0.41, 0.91)*	0.60 (0.05, 1.16)*	1.83 (1.06, 3.18)*
20–40%	–0.66 (–1.30, –0.03)*	0.51 (0.27, 0.97)*	0.61 (0.26, 0.97)***	1.85 (1.30, 2.63)***
0–20% most deprived	–1.00 (–1.59, –0.42)***	0.37 (0.20, 0.65)***	0.57 (0.13, 1.00)**	1.76 (1.14, 2.73)**
Ethnicity				
White	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
Non-white	–0.06 (–0.48, 0.35)	0.94 (0.62, 1.42)	–0.23 (–0.67, 0.21)	0.80 (0.51, 1.24)
Frequency of brushing teeth				
Twice a day or more	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
Once a day or less	0.22 (–0.08, 0.53)	1.25 (0.92, 1.69)	0.03 (–0.27, 0.33)	1.03 (0.76, 1.40)
Frequency of sugar intake				
<4 times a day	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
4 or more times a day	0.55 (0.26, 0.84)***	1.73 (1.29, 2.33)***	0.44 (0.09, 0.78)*	1.55 (1.10, 2.18)*
Usual dental attendance				
Regular	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
Irregular/none	0.77 (0.45, 1.10)***	2.17 (1.57, 3.00)***	0.74 (0.35, 1.14)***	2.11 (1.42, 3.14)***
Self-rated dental anxiety score MDAS grouping				
Low/no anxiety (score 5–9)	1.00 (reference)	1.00 (reference)	1.00 (reference)	1.00 (reference)
Moderate anxiety	–0.31 (–0.58,– 0.03)*	0.74 (0.56, 0.97)*	–0.40 (–0.69, –0.11)**	0.67 (0.50, 0.9789)**
Extreme anxiety	0.40 (–0.11, 0.91)	1.49 (0.890, 2.48)	0.08 (–0.37, 0.52)	1.08 (0.69, 1.69)
/cut1			2.70 (1.51, 3.89)	
/cut2			4.22 (2.97, 5.47)	
/cut3			7.16 (5.89, 8.43)	

OR, odds ratios; CI, confidence intervals; MDAS, Modified Dental Anxiety Scale; ICDAS, International Caries Detection and Assessment System. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$. [a] Unadjusted and full-adjusted ordered logistic regression models were fitted, and OR were reported.

Table 5. Predicted proportion of categories of highest and lowest OR in each variable estimated by full-adjusted ordered logistic regression model under *clinical* (ICDAS 1–6) and *obvious* (ICDAS 4–6) *decay* thresholds

	Low DE proportion % (95% CI)	Medium DE proportion % (95% CI)	High DE proportion % (95% CI)	Extremely high DE proportion % (95% CI)
Clinical decay (ICDAS 1–6) threshold				
Categories of the highest OR	4.00 (1.03, 6.97)	17.35 (7.60, 27.10)	58.80 (52.27, 65.34)	19.84 (8.62, 31.08)
Categories of the lowest OR	90.22 (80.16, 100.28)	8.14 (–0.14, 16.43)	1.52 (–0.16, 3.21)	0.11 (–0.03, 0.26)
Obvious decay (ICDAS 4–6) threshold				
Categories of the highest OR	6.96 (2.93, 10.98)	18.56 (9.88, 27.24)	61.06 (53.95, 68.17)	13.42 (3.37, 23.46)
Categories of the lowest OR	93.10 (87.36, 98.85)	5.31 (0.78, 9.83)	1.51 (0.30, 2.71)	0.09 (0.00, 0.17)

Low DE, low decay experience; medium DE, medium decay experience; high DE, high decay experience; extremely high DE, extremely high decay experience; OR, odds ratios; CI, confidence intervals; ICDAS, International Caries Detection and Assessment System.

Clusters of Caries Experience

Hierarchical clustering analysis, taking account of conceptually staged caries thus grouping individuals based on their decay experience with no a priori pattern definition, was a novel attempt to identify patterns of adolescents more vulnerable to caries at population level to inform policy and action. This study suggested that within these UK adolescents, there are 4 clusters rather than 3 as suggested globally [Sheiham and Sabbah, 2010], Broadbent et al. [2008] in New Zealand and Warren et al. [2017] in Iowa, USA, and 5 by McDonald and Sheiham for the USA [Sheiham and Sabbah, 2010]. This may be related to methodological or context/setting differences between studies. Caries experience represents the cumulative effects of risk factors to which individuals have been exposed. Therefore, using hierarchical clustering analysis in cross-sectional surveys provides insights into the proportion of the population that require additional resources for appropriate treatment regimens and recall intervals, with a view to informing action and proportionate investment of resources to alter their risk and life-course trajectory.

Whereas adolescents assigned to the same cluster shared a similar caries pattern, patterns of caries-affected tooth surfaces and their prevalence were different among clusters. Clustering focused on overall caries status, so when compared with other decay diagnostic thresholds, merely considering *cavitated* criteria clustered cases with more serious dental caries in a lower decay experience group, which may lead to underestimate the level of disease severity. On the contrary, *clinical* criteria identified some cases with multiple initial stage caries into a high decay level group.

Factors Associated with Dental Caries Clusters at Different Thresholds

There were clear inequalities in caries experience by socioeconomic conditions and geography. This suggests that there is much public health action required at local level to understand the impact of context and how this can be addressed. It would be appropriate to explore doing this in relation to other public health issues such as obesity [WHO, 2015; PHE, 2020]. There is a clear north/south divide within England and between UK countries. The need for family- and population-level interventions to address these differences has already been recognized [O'Malley et al., 2018]. Generally, 2 strategies are considered to develop prevention approaches. One may target an entire population to assure equity, and another one may target high-risk groups for better cost-effectiveness [Pitts et al., 2017]. Proportionate universalism combines these approaches in a population strategy [Francis-Oliviero et al., 2020].

A crucial behavioural factor is sugar intake. Adolescents who consumed sugary diets 4 times or more a day were 1.5 times more likely to experience dental caries than those with lower less sugars intake. The WHO strongly recommends that individuals should limit consumption of free sugars throughout their life course to <10% of total energy intake and lower to 5% total energy intake for further benefits [WHO, 2015]. Data from the National Diet and Nutrition Survey (NDNS) within the UK in 2012/2013–2013/2014 revealed that 11–18 year olds had a sugar intake 3–5.5 times higher than the maximum WHO recommendation [PHE, 2016; Lai et al., 2019]. The UK has important ongoing strategies to curb sugar intake, including the levy on sugary drinks, the reduction of sugar in the food industry via the recent Sugar reduction Programme [PHE, 2020], and changing the sugar consumption behaviours of children via *Change4Life* programme which was launched in 2009 [NHS, 2020]. However, adolescent health behaviours remain a challenge [O'Malley et al., 2018; NHS, 2020], with areas such as restricting sugar consumption not attracting the same level of importance for parents and children [O'Malley et al., 2018], since peer support becomes increasingly important as they develop independence from their parents [WHO, 2017]. Dental attendance pattern presents a challenge in relation to dental care as children who suffer from more severe level of decay are much less likely to be regular dental attenders. Longitudinal research shows the benefits of dental attendance in a high-income country [Thomson et al., 2010; Crocombe et al., 2012]. Methods of reaching out to younger people during this transition phase of life should be explored in support of oral health, particularly because those who most need care will be more likely to present for emergency care and possibly require admission for treatment under sedation or general anaesthesia. Adolescents who had moderate dental anxiety were more likely to be allocated to lower caries-affected clusters. The Dunedin study identified 6 dental anxiety trajectories; members of the stable non-anxious medium trajectory and the late-adolescent-onset anxious trajectory had medium-level dental anxiety at the age of 15 years, and a medium-level mean DMFS score [Thomson et al., 2009]. Adolescents might have a rising awareness of oral health care, and more chance of using dental services, possibly receiving orthodontic treatment and preventive measures.

Certain limitations of this study need to be acknowledged. First, we used cross-sectional data, which does not allow to make inferences about caries risk, for which incidence data are paramount. However, predictors were chosen based on the current understanding of caries epidemiology. The present findings await confirmation from longitudinal studies among adolescents. Second, some adolescents (10.7%) were excluded from the analysis because of missing values on relevant variables, which might raise some concerns about generalizability. We found differences between the cases included and excluded, especially in terms of geographical representation. This implies that the sample was representative of the adolescent population in England, but less so of those in Wales and Northern Ireland. Third, dental caries was diagnosed using the visual-tactile method and without the aid of radiographs. Although this is the standard approach in large epidemiological surveys, it can underestimate the prevalence of dental caries, especially of early lesions in proximal surfaces. Also, in epidemiological field conditions, ICDAS 1 is likely to be underscored. These issues could influence the identification of clusters at the lowest threshold (ICDAS 1–6) but is less likely to affect it at higher thresholds.

The present findings have several significant implications for public health policy. First, oral health inequalities in children and young people lead to unmet health care needs, particularly in those at higher risk who are least likely to attend for dental care. It would be interesting to explore the reasons for their dental history and work with them to consider how this might be changed. Hierarchical clustering analysis provides a way to group individuals according to their decay experience with no a priori pattern definition. It provides insight to the nature and level of resources, then specific prevention, and treatment implementations, or policies could be produced targeting resources to different clusters cost-effectively [Pitts et al., 2014]. Adolescents with high, or extremely high, level of caries experience require specific support. Second, given that dental caries severity increases with age, all children and young people require preventive support in a universal manner. Third, it should be noted that in England and Wales, there is greater emphasis on risk assessment tools, which should be encouraged. With the help of the model we established, the local authorities from all countries including Scotland and Northern Ireland could identify adolescents with highest decay risks without oral screening. It will be particularly important for dental teams to build active links with these adolescents and support them on a path to better oral health. Lastly, this was an attempt to explore the caries patterns among one specific population, expanding the application to other populations will be important in future research.

This research highlights the importance of recognizing the dental caries process in epidemiological surveys and suggests that adolescents fall into 4 clusters from low to extremely high risk, regardless of the decay threshold. It also provides insight to the nature of adolescents in each of the clusters and as such is a helpful approach in national survey analysis to inform research, policy, and action.

Acknowledgments

UK national oral health survey team and public data service made these data available for secondary analysis. https://beta.ukdataservice.ac.uk/datacatalogue/studies/study?id=7774&type=Data%20catalogue.

Statement of Ethics

The original survey was subject to ethical review by the University Ethics Committee at University College London (Project ID 2000/003). Written consent was obtained for the primary data collected. Further ethical clearance was not required since the present study was based on a secondary analysis of data provided by the public UK data service website.

Conflict of Interest Statement

J.E.G. is employed full time by King's College London. She is funded through Newland-Pedley Endowment from King's College London and Public Health England. She is a honorary consultant in Dental Public Health with the NHS Hospital Trusts of KCHFT and GSTT and Honorary Consultant to Public Health England; she is a visiting professor of Dental Public Health, Oman Dental College, Muscat, Oman. J.E.G. has received research funding from the UK National Institute of Health Research, Wrigley, GSK, and King's College London. J.E.G. is a chair of the consultants' group of BASCD. X.Z.W. is employed full time by Peking University School and Hospital of Stomatology. Over the last 3 years, she has received research funding from the Peking University School and Hospital of Stomatology. She was a visiting researcher in the Faculty of Dentistry, Oral & Craniofacial Sciences, King's College London in 2017/18. E.B. is employed full time by King's College London and has an Honorary Academic contract with Public Health England. N.P. is employed full time by King's College London. He was part of the Consortium that undertook the 2013 Children's Dental Health Survey. Over the last 3 years, he has had consultancies with Colgate, GSK, and Calcivis and owns stock in King's Spin-out Companies Reminova and NirVisio; he has received research funding from the UK National Institute of Health Research. Nigel is a chair/co-chair of 3 research implementation charities associated with King's College London: the ICDAS Foundation, the Alliance for a Cavity Free Future, and the Erosive Tooth Wear Foundation. S.G.Z. is employed full time by Peking University School and Hospital of Stomatology. Over the last 3 years, he has received research funding from the National Natural Science Foundation of China, the Ministry of Science and Technology. He is the office director of The World Health Organization Collaborating Center (WHOCC) for the Research and Training in Preventive Dentistry in China, and the Chairman of the Stomatological Society of Chinese Association for Improving Birth Outcome and Child Development.

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Author Contributions

J.E.G. contributed through devising the project, research design, data interpretation, drafting, and revising of the manuscript. X.Z.W. conceptualized and designed the research, conducted the data analysis, visualized the results, original drafted, and revised the manuscript. E.B. advised on the research design, conducting, and validating data analysis, data interpretation, and manuscript revision. N.P. assisted with the design of the project and provided insights to the national survey methodology and data. N.P. and S.G.Z. made intellectual contribution on interpretation of data, critically reviewing, and editing the manuscript. All authors have read, reviewed, and approved the final version of the paper.

Data Availability Statement

The original data of CDHS 2013 were downloaded from: https://beta.ukdataservice.ac.uk/datacatalogue/studies/study?id=7774&type=Data%20catalogue with registration and authentication. These safeguarded data were authorized to be used for non-commercial, commercial, and teaching projects.

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