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Time and Temporality as Categories of Connectedness

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Time-Respecting Paths in Letter Networks Reveal Opportunities for Influencing Information Transmission during the European Reformation

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Abstract Information transmission shapes society by fostering innovation, as well as cultural growth. While previous studies have used aggregated networks and temporal network snapshots to study this transmission, they either overlook the timing of interactions entirely or consider it only broadly, which can distort topological network measures and bias conclusions. This study addresses this limitation by analyzing information transmission using time-respecting paths – sequences of nodes connected by time-consecutive edges within specific time bounds. By examining these paths in a letter correspondence network of 16th-century Protestant reformers, this work identifies the reformers' potential influence on information transmission across three dimensions: information access, the establishment of resilient communication paths, and control of communication paths. Results reveal one low-potential group and two medium-potential groups – one leveraging short, redundant paths for resilience, the other occupying key intermediary positions for control. The results provide the first step towards understanding how these reformers leveraged and overcame the behavioral options provided by their network positions.

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Introduction

Information exchange is essential for driving social change,[1] but for information to have a transformative impact, it must reach and be adopted by a large audience.[2] During the Reformation in 16th-century Europe, ideas such as the Bible being the sole authority in matters of faith, or political independence from the Church and Emperor, sparked profound societal shifts,[3] including the rise of literacy,[4] the emergence of nation-states,[5] and the split between Catholics and Protestants.[6] The spread of these ideas relied on the transmission of information, mainly via face-to-face interactions and letters.[7] By studying how individuals contributed to this transmission of information, we can gain a clearer understanding of how social change may have occurred.[8]

Research on social relationships demonstrates that the structure of an individual's social network and their position within it are key to successful information transmission.[9] For instance, nodes that bridge disconnected clusters facilitate the spread of information,[10] while peripheral nodes can help achieve wide-scale dissemination.[11] A popular approach is to study information transmission in communication networks, where nodes represent individuals and edges represent exchanged messages,[12] with historical studies often examining letter correspon-

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1 Enthoven 2022, 246–248.
2 Buskens and Yamaguchi 1999, p. 282; Rogers 2003, pp. 154–156; Guilbeault et al 2018, pp. 7–9.
3 Shelley 2013, p. 247.
4 Becker and Woessmann 2009, p. 532.
5 Reinhard 1999, pp. 397–398; Schilling 1992, p. 209.
6 Heal et al 2014, pp. 586–589.
7 van Miert et al 2019, p. 34.
8 Buskens and Yamaguchi, "A New Model," 321–323.
9 Freeman 1979; Guilbeault et al. 2018, p. 3.
10 Burt 2004.
11 Steinert-Threlkeld 2017; Clarke 2014; González-Bailón et al. 2013.
12 Ahnert and Ahnert 2014, pp. 4–5; Diesner et al. 2014.

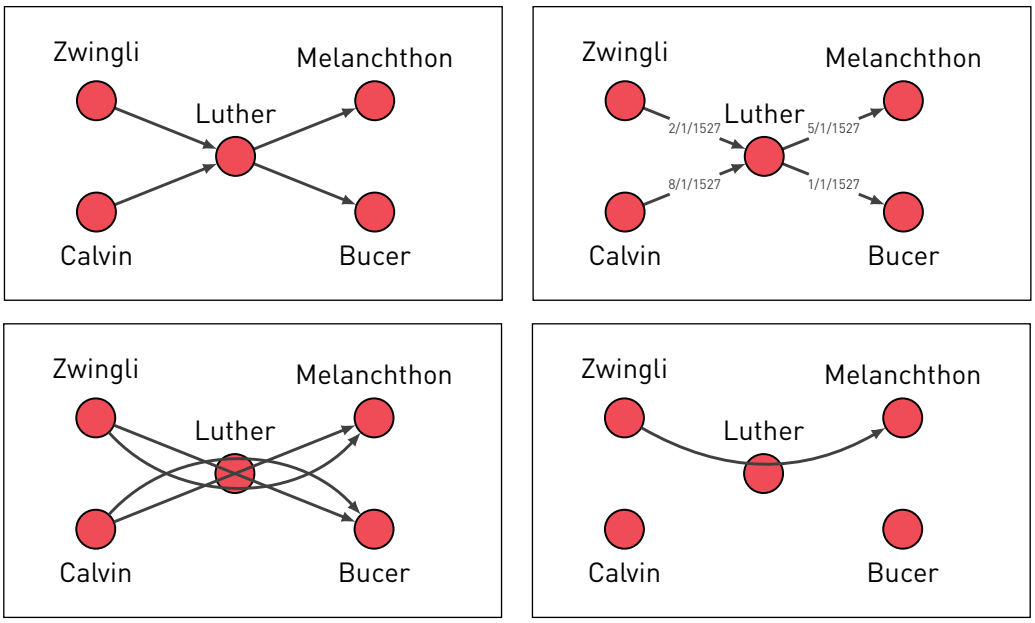

Fig. 1 Betweenness scores differ when computed on the aggregated network (a, c) and when accounting for time-stamped edges (b, d).

dence networks.[13] Traditionally, these analyses use aggregated networks that ignore edge timestamps, or temporal network snapshots that only capture edge chronology between – not within – snapshots. In aggregated networks and within individual snapshots, it is implicitly assumed that incoming messages precede outgoing ones to enable information flow.

However, in aggregated networks and within snapshots this assumption is often violated. Since time is ignored, the chronological ordering of edges may be broken, which biases topological network measures.[14] Figure 1 visualizes this problem with letter exchanges between five Protestant reformers in an aggregated network, using the topological network measure of betweenness centrality as an example. The betweenness centrality of a node *i* counts the shortest number of paths that link any two node pairs and run via node *i*.[15] Given that information is assumed to be passed on via shortest paths, *i*'s betweenness is interpreted as the amount of information *i* passes on from one node to another. If one ignores time and computes the betweenness centrality of Luther, one sees that Luther connects all four other node pairs via the shortest connections (Fig. 1c). His betweenness is thus four. In contrast, if one considers time by including the send-

13 Ahnert and Ahnert 2014, pp. 4–30; Ahnert and Ahnert 2019.
14 Scholtes et al. 2016, pp. 1–2.
15 Freeman 1979, p. 223.

ing dates of letters as edge time stamps (Fig. 1b), Luther only connects one node pair: Zwingli and Melanchthon. For the other node pairs, Luther sends his outgoing letters before receiving the incoming ones, and hence cannot pass on information. Luther's betweenness decreases to one (Fig. 1d). This example shows that, in the aggregated network, connections mediated by Luther can run backwards in time, which overestimates Luther's role in the transmission of information.

Previous research has proposed a variety of methods to incorporate time in networks.[16] Among the most popular approaches, especially in historical network research, is the temporal snapshot approach. This splits the observation period into time slices and aggregates the nodes and edges inside each time slice into subnetworks. The main challenge is to choose the size of the time slices, and approaches range from purely data-driven[17] to more theory-driven methods.[18]

In historical network research, time slices correspond to diverse categories, including Chinese dynasties,[19] the periodization of global history,[20] decisive moments in the planning of Hitler's assassination,[21] and movements that helped Jews to hide in World War II,[22] the smallest temporal unit in the data (e.g., years),[23] and periods based on informed reasoning,[24] as well as periods that facilitate visualization.[25] However, since subnetworks are aggregated, the snapshot approach has the same problem as the global aggregated network: the temporal ordering of edges is not preserved within a snapshot, allowing the transmission of information to run backwards in time.

In this article, I address this problem by analyzing time-respecting paths in a letter correspondence network of Protestant reformers. A time-respecting path is a sequence of nodes that are connected by time-consecutive edges (e.g., Zwingli → (1st January 1527) Luther → (5th January 1527) Melanchthon in Figure 1d) with the inter-edge time being bounded, i.e., the time passed between two consecutive edges must neither be too small nor too large. Time-respecting paths preserve the temporal ordering of edges and therefore represent potential routes for information transmission. Whether these paths were actually used can be veri-

16 Holme and Saramäki 2012; Holme 2015, pp. 4–14; Williams et al. 2022, pp. 2–4; Peixoto and Gauvin 2018): 1–8.
17 Darst et al 2016, pp. 2–3; Peixoto and Gauvin 2018, pp. 1–8.
18 Lemercier 2015, pp. 4–15.
19 Bingenheimer 2021, p. 237.
20 Petz et al. 2020, p. 341
21 Conroy et al. 2022, pp. 97–99.
22 Düring et al. 2011, pp. 439–440.
23 Gilles 2020, p. 118; Buch-Hansen and Grau Larsen 2021, p. 7.
24 D'haeninck et al. 2015, p. 117.
25 van Vugt 2017, p. 34.

fied by examining if information from letter texts followed these routes, though this extends beyond the scope of this paper and will be subject to future research.

In this paper, I use time-respecting paths to assess three key aspects of reformers' potential impact on information transmission: (1) access to information enhancing opportunities for generating new ideas;[26] (2) establishment of resilient communication paths for secure transmission;[27] and (3) control over existing paths to influence or obstruct others' communication.[28]

To the best of my knowledge, this study is the first to apply time-respecting paths to network analyses of historical data. It addresses problems of standard temporal network approaches such as the temporal snapshot approach and contributes to the overall question of how to account for temporal information in quantitative historiographical research.

Letters and Their Analysis

Sources

I use letters from three types of sources: First, I crawled public online repositories which published the partial or complete letter editions of seven Protestant reformers. These crawls resulted in 19,430 letters: Martin Luther: 3,886;[29] Philipp Melanchthon: 8,854;[30] Huldrych Zwingli: 929;[31] Heinrich Bullinger: 3,028;[32] Martin Bucer: 991;[33] Oswald Myconius: 1,740;[34] and Andreas Karlstadt:

26 Granovetter 1973, p. 1371; Björk and Magnusson 2009, p. 665; Bakshy et al. 2012, p. 526.
27 Centola and Macy 2007, 709–710; Jenssen and Greve 2002, p. 261.
28 Burt 2004, p. 353; Lee et al 2023, p. 3716.
29 ProQuest, "Luthers Werke," Last access: 06/12/2017, n.d. Database, https://www.proquest.com/luther/index.
30 Heidelberg Academy of Sciences and Humanities, "Melanchthons Briefwechsel – Regesten online," Last access: 07/12/2017, n.d. Database, https://melanchthon.hadw-bw.de/index.html.
31 Institute for Swiss Reformation Studies, University of Zurich, "Huldrych Zwingli Briefe: Digitale Texte," Database. Last access: 04/12/2017, n.d. Database, https://www.irg.uzh.ch/static/zwingli-briefe/index.php.
32 Institute for Swiss Reformation Studies, University of Zurich, "Heinrich Bullinger Briefwechsel (1524–1575)," Last access: 01/12/2017, n.d. Database, http://teoirgsed.uzh.ch/.
33 Bucer Forschungsstelle, University of Erlangen, "Martin Bucers Briefkorrespondenz," Originally at: http://www.bucer-forschungsstelle.theologie.uni-erlangen.de/. Last access: 04/12/2017, n.d. Database, https://augustana.de/forschung-lehre/kirchengeschichte/bucer-forschungsstelle.html.
34 University Library Basel, "Oswald Myconius: Korrespondenz," Last access: 01/12/2017, n.d. Database, https://basel.swisscovery.org/discovery/search?query=any,contains,Oswald%20Myconius&tab=UBS&search_scope=UBS&vid=41SLSP_UBS:live&mfacet=rtype,include,correspondence,1&offset=0.

96.[35] Second, I received manually digitized letters from historians: 515 letters from Johannes Oekolampad and 1943 letters from Joachim Vadian,[36] as well as 8,670 additional letters from Philipp Melanchthon.[37] I refer to the nine reformers whose letter editions or selected letters I used as the 'selected reformers'. Third, I digitized the metadata of 10,093 unpublished letters from the Bullinger edition, which were provided in the form of analogue flashcards (for an example, see Section 1.1 in Supplementary Material).[38]

In total, the data consist of 26,663 letters exchanged between 3,370 individuals, sourced from the editions of nine selected reformers. It includes information on senders, recipients, and letters. For this analysis, I focused on three attributes: sender and recipient names, and sending dates. To ensure data completeness, only letters with non-missing values for these attributes were included, resulting in a final dataset of 26,558 letters and 3,348 individuals. While this approach may introduce selection bias, it was a practical choice, the consequences of which are discussed in Section 2.2. A detailed description of the attributes, missing values, and data model is provided in Section 1.2 of the Supplementary Material.

The data contain inconsistent entries on names, locations, and dates. In the 16th century, spelling was not standardized, and correspondents often used synonyms to evade censorship.[39] Digitized letter editions sometimes provide ambiguous dates and locations as estimates for missing data, such as "around Christmas 1520" or "in the vicinity of Vienna". I disambiguated the data in a semi-automated manner to obtain unique entities for persons, dates, and places.

Persons. I matched the aliases of sender and receiver names to the same unique person by using the editing distance (Levenshtein distance).[40] If the editing distance was smaller than three characters, I matched the two names to the same person. Otherwise, the two names were presented to a historian who manually disambiguated them. The dataset contained 3,629 unique names (including aliases), resulting in 13,166,012 potential name pairs ($3{,}629^2 - 3{,}629$). 99.98% of

35 Thomas Kaufmann (ed.), "Kritische Gesamtausgabe der Schriften und Briefe Andreas Bodensteins von Karlstadt, Teil I (1507–1518) (Editiones Electronicae Guelferbytanae)," Last access: 05/12/2017, 2012, Database, http://diglib.hab.de/edoc/ed000216/start.htm.

36 Vadian and Oekolampad Korrespondez, Vadian and Oekolampad correspondences, 1500–1551, Received from Amy Burnett on October 30, 2019, unpublished dataset.

37 Melanchthon Korrespondenz, Melanchthon correspondences, 1514–1560, received from Christine Mundhenk on March 10, 2019, unpublished dataset.

38 Bullinger Korrespondenz, Bullinger correspondences, 1547–1575, received from Reinhard Bodenmann on September 15, 2020, unpublished dataset.

39 Hotson et al 2019, pp. 120–122.

40 The Levenshtein distance corresponds to the number of characters that need to change in one name to receive the second name.

these pairs had a Levenshtein distance greater than three and had to be manually disambiguated. However, this does not mean that the historian had to check millions of name pairs, since matched aliases were removed from future comparisons thereby steadily reducing the number of name pairs to be checked. For instance, once 'Martin Luther' and 'Martin on the Wartburg' were matched, only 'Martin Luther' was compared to remaining names.

Dates. I matched ambiguous sending dates to unique day-specific timestamps by using hard-coded rules. If a selection of dates ('1st June 1520 or 1st July 1520') or a period was given ('June 1520'), I chose one date uniformly at random from all the possible dates. If a reference to a cutoff date was mentioned ('before 1st June 1520'; 'around Easter 1520'), I matched keywords (e.g., prepositions and holidays like Easter) to fixed date ranges and chose one date uniformly at random from these.

Places. I matched sending and receiving locations to a unique geo-location (longitude and latitude) with the Google Maps API.[41] I plotted the received geo-locations on a map and corrected outliers manually, including locations outside of Europe (e.g., 'Base' was mapped to a military base in Oklahoma, US instead of to the city of Basel). I conducted random spot tests and checked whether the assigned geo-location matched the location name mentioned in the letter. The major challenges in disambiguating places include spelling mistakes ('Base' instead of 'Basel'), homographs (words that are spelled the same but have different meanings, like the cities of 'Frankfurt', where one is located in the South-West and the other in the North-East of Germany), and similar but nonidentical names of different locations ('Wittenberg' vs 'Wittenberge'). Places were utilized solely for exploratory analysis to inform the selection of path parameters (see Section 2.1 in Supplementary Material), but they were not directly incorporated into the construction of time-respecting paths.

Since standardization procedures like EMLO were not fully developed at the time of data pre-processing,[42] I opted not to use them. Instead, I standardized individuals using DNB links from the German National Library.

41 Google, "Google Maps," Last access: 05/09/20109, n.d., API. https://developers.google.com/maps/documentation, 2005, visited on 05/09/2019.

42 Howard Hotson and Miranda Lewis, "Early Modern Letters Online," Last access: 01/02/2025, n.d., Database. http://emlo.bodleian.ox.ac.uk.

Letters for 16th-Century Reformers

In 16th-century Europe, letters were the primary written communication among scholars.[43] Despite rising literacy during the Reformation,[44] letter-writing remained the domain of political and academic elites, who idealized their exchanges as the "Republic of Letters" – an open-minded network for discussing science and politics to advance human progress.[45] In reality, access was limited by social rank,[46] content was often censored by the Catholic Church and political leaders,[47] and letters also addressed mundane topics like administrative issues, personal matters, and polemics.[48] In short: letters were an important means to transmit information.

For 16th-century reformers, letters served multiple purposes, depending on their various roles. As church scholars, reformers used letters to instruct local authorities (e.g., pastors) on how to implement church ordinances, prepare disputations and discuss their outcomes with other scholars, and provide feedback on other scholars' work. Often, criticism was personal, attacking the author rather than his work; polemic was an established stylistic device leading to "wars of intellectual exchange".[49] For example, Martin Luther provided pastoral guidance on matters of spirituality in letters to lay people and the clergy,[50] and the Swiss reformers Calvin and Bullinger engaged in correspondence over interpretations of the Eucharist, culminating in the Consensus Tigurinus, a joint statement on sacramental doctrine.[51]

As political advisors, reformers used letters to prepare imperial diets and disseminate their outcomes, request favors from political rulers (e.g., money), convince them of their theological views, advise them on hiring decisions of other reformers, and recommend friends to university or political positions. For example, Philipp Melanchthon and other reformers refined theological arguments in letters exchanged with Martin Luther in preparation for the Diet of Augsburg (1530), which Luther could not attend due to the imperial ban.[52] This correspondence led to the Augsburg Confession, the foundational document of Lutheranism, presented to Emperor Charles V at the diet. Additionally, Calvin used letters

43 van Miert et al. 2019, p. 34.
44 Becker and Woessmann, 2009, pp. 539–542.
45 van Miert et al. 2019, p. 27.
46 van Miert et al. 2019, pp. 27–30.
47 van Miert et al. 2019, p. 36.
48 Matthews-Schlinzig 2019, pp. 76–77.
49 van Miert et al. 2019, p. 36.
50 Tappert 2003.
51 Campi 2016, pp. 11–15.
52 Wicks 1980.

to advise King Edward VI on how best to protect the purity of the gospel in England.[53] Finally, reformers like Karlstadt and Melanchthon received university appointments through recommendations from Luther.[54]

As private individuals, reformers maintained friendships and family ties through letters, often including material gifts. For example, Swiss reformer Heinrich Bullinger sheltered English refugees during Queen Mary I's reign and remained in contact with them after their return to England.[55] His correspondence included gifts such as cheese, wine, clothing, and money.[56]

Besides these communicative purposes, reformers also adopted particular styles when exchanging letters. One of the strongest norms was reciprocity, where recipients were expected to respond to letters they received.[57] However, many individuals only kept incoming letters, making it difficult to fully reconstruct their exchanges. Correspondence often involved collectives, with letters being sent by or addressed to groups rather than individuals. When a letter was intended for multiple recipients, it might be passed from one person to another, with specific sections highlighted for different individuals, sometimes even in different languages. For instance, Latin was used for political discussions with a prince's secretary, while German was reserved for more private matters with his wife.

Transport played a crucial role in facilitating the exchange of information across Europe. Letters were sent using a variety of transport modes depending on the distance and resources available.[58] When people relocated due to work or exile, letters became the primary means of maintaining contact with distant family and friends, or asking patrons for financial support.[59] Letters were often entrusted to friends or students who happened to be traveling towards the recipient's location.[60] Over time, a postal network emerged, utilizing stagecoaches for delivery,[61] although the political elite could also make use of private couriers on horseback.[62] These varied methods of transport led to significant differences in travel times,[63] complicating the effort to model the communication paths reformers used to exchange information, as I will explore further below.

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53 Robinson 1846, p. 709.
54 Ilardi 1987, p. 1128.
55 Lowe 2017, pp. 181, 184, 191, 196, 198.
56 Giselbrecht 2014, p. 49
57 van Miert et al. 2019, p. 26.
58 Tessier 2019, p. 333.
59 Janssen 2014, pp. 61, 75.
60 Kim and Pfaff 2012, p. 190.
61 Schobesberger et al. 2016, p. 21
62 Tessier 2019, p. 333.
63 Tessier 2019, p. 340.

In conclusion, letters were a crucial tool for scholarly communication in 16th-century Europe, shaped by social hierarchies, censorship, and practical constraints. Reformers used them in various roles – church scholar, political advisor, and friend – adopting communication styles that emphasized reciprocity, collective exchanges, and multi-lingual letters. The diversity of transport methods complicates the reconstruction of information transmission.

Limitations of the Letter Data Set

Using letters as data presents significant challenges, both generally and within this analysis. Generally, letters are subject to survivor bias, meaning the available sources reflect what has survived rather than what was actually written. This bias can arise for various reasons, such as letters being destroyed to avoid persecution, protect reputations, or align with political shifts, and reciprocated letters are often missing since many individuals kept only incoming mail. Survivor bias makes it impossible to determine the ground truth or assess absolute data quality. Comparing multiple datasets allows us to evaluate relative quality and select the most reliable available source.

The letter data in this analysis are affected by selection bias, missing values, and measurement errors. Selection bias in this study arises primarily from the availability of digitized letter collections, which tend to favor well-known individuals due to resource constraints and historical interest. This study, limited to letters from nine prominent reformers whose collections were available during data collection in 2017, does not offer a representative sample of Reformation era correspondence. While more comprehensive datasets have since emerged,[64] they remain incomplete, reflecting the evolving nature of data accessibility.

Selection bias in this study has two key consequences: first, the dataset's narrow scope prevents broad generalizations about 16th century correspondents, underrepresenting lesser-known figures. Second, missing correspondences distort network structures. The absence of peripheral figures leads to loosely connected star networks where peripheral nodes are barely interconnected (superposition of ego-networks), affecting measures like centrality and path lengths, although degree-correction can mitigate this bias.[65]

Many letters in the dataset lack key metadata, such as dates and sender and recipient names. These gaps may stem from digitization errors or omissions in the original documents. A major challenge is the absence of receiving dates, which complicates the analysis of communication paths, as it remains unclear when in-

64 Hotson and Lewis, "Early Modern Letters Online."
65 Ahnert and Ahnert 2019, p. 35.

formation became available for further dissemination. Estimating these dates is difficult due to the unknown transport modes and thus travel times of letters.

Missing sending dates prevent the extraction of time-respecting paths, while missing sending and receiving locations hinder the automatic derivation of path parameters like maximum inter-edge times (see Section 2.1 in the Supplementary Material). This restricts the validation of these parameters.

To ensure consistency, I excluded letters missing senders, recipients, and sending dates. This approach introduces selection bias if the letters omitted systematically differ from those retained, skewing the dataset's composition. Despite this limitation, exclusion was necessary to maintain analytical robustness, given the difficulty of approximating missing dates reliably.

Since the reasons for missing metadata remain unclear, it is uncertain whether these gaps are random or reflect biases tied to individuals, institutions, or historical periods.[66] Expanding digitization efforts for letters from underrepresented individuals addresses part of the issue. The other part lies in conducting robustness checks, comparing the same analysis across different letter datasets in contexts where similar social behavior is expected.

Measurement error arises from both digitization and disambiguation processes. Digitization errors can occur due to incorrect OCR or mistakes during manual data cleaning, which result in misinterpreted metadata when extracting information from scanned letters. Since most letters were pre-digitized, I had limited control over these biases, making them an inherent constraint of the dataset.

Disambiguation errors arise because I rely on random selection to resolve entities. While necessary for processing efficiency, this introduces uncertainty, as the chosen entity may not be that which is historically correct. To assess the impact of disambiguation errors, future research could conduct robustness checks by generating multiple dataset versions from ambiguous entries and running the same analysis on each. If the results remain consistent, this would suggest that disambiguation choices do not significantly affect conclusions. However, this approach only ensures stability, not correctness, as the accurately disambiguated dataset might not be among the tested versions, potentially yielding different results. The fundamental issue is that the extent of measurement error remains unknown. Without a method to validate disambiguated entries systematically, it is difficult to assess whether errors are minor or significant enough to distort findings.

66 Ureña-Carrion et al 2022, p. 4.

Given these biases, the accuracy of sending dates – and consequently the temporal ordering of letter transmissions – is uncertain. This significantly limits the interpretation of time-respecting paths as channels of potential information transmission. As a result, this study does not allow us to make strong inferences about the population or sample of 16th-century reformers. Instead, the findings should be viewed as an illustration of the method, rather than a definitive reconstruction of historical communication practices. Future studies applying path-based methods should rely on datasets with higher relative quality, incorporating broader letter collections for generalizability and improved metadata for exact sending dates.

Operationalizing the Letter Data as Network

Conceptualizing Time-Respecting Paths

Based on the proposition that letters acted as a medium of information transmission during the Reformation, two implications follow: first, an incoming letter must result in an outgoing letter with the same information; and second, the outgoing letter has to be sent within a certain time window reflecting the minimal reaction time and memory of the recipient.[67]

These implications are captured in the time-respecting paths which I extract from the letter correspondence network of reformers. A time-respecting path is a sequence of nodes that are connected by time-consecutive edges (chronology) with the inter-edge time being restricted by a lower (minimal reaction time) and upper bound (memory).[68] For example, the connection Zwingli → (2/1/1527) Melanchthon in Figure 1d represents a time-respecting path if information from Zwingli's letter from 2nd January 1527 was not forgotten by 5th January 1527, so Luther can then pass the information on in his letter to Melanchthon. Figure 2 shows that time-respecting paths are broken if either the edge chronology is not preserved or too little/too much time passes between two consecutive edges. An important property of time-respecting paths is their path length, which corresponds to the number of edges connecting sequential nodes (Fig. 3).

Time-respecting paths are useful because they improve centrality measures compared to aggregated networks (see Figures 1 and Scholtes, Wider and Garas, 2016[69]). If the temporal ordering of edges is not preserved measures like betweenness centrality may be overestimated, making reformers seem more influential in terms of their impact on information transmission.

67 Petrović et al. 2023, p. 2.
68 Pfitzner et al. 2013, p. 1; Holme and Saramäki 2012, p. 3.
69 Scholtes et al. 2016, pp. 6– 13.

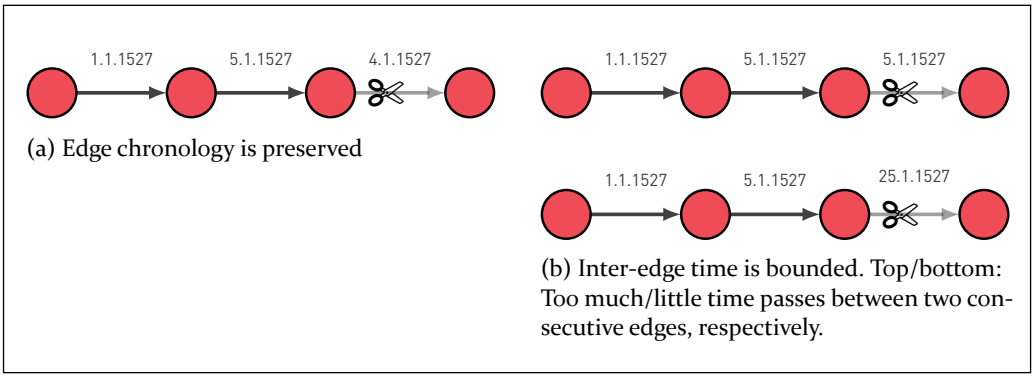


Fig. 2 Properties of time-respecting paths.

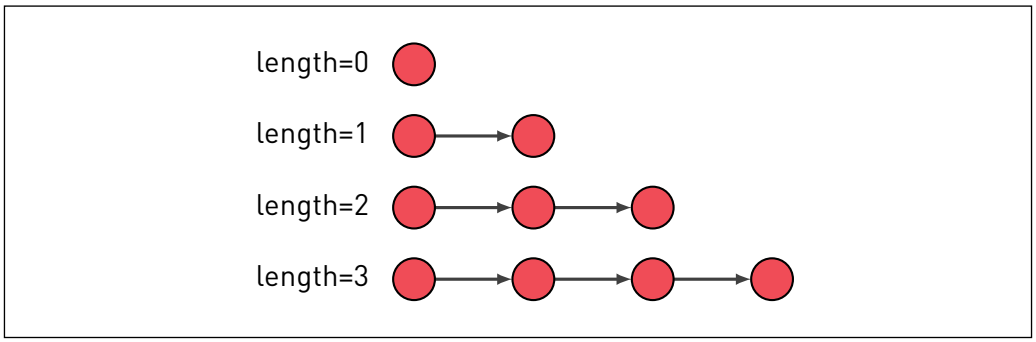


Fig. 3 The length of a time-respecting path corresponds to the number of edges connecting the sequence of nodes.

Whereas extracting chronological edges from a communication network is straightforward, choosing the correct bounds of the inter-edge time to account for reaction time and memory is not. The timescale at which temporal edges influence each other is unknown,[70] i.e., whether reformers pass on information from letters that they received five days, five months or five years ago. Moreover, the travel times of letters affect the relevant timescale, as a recipient can only forget the information in a letter during the interval between receiving it and sending a new one. I refer to this interval as the 'waiting time' (Fig 4). Since my data only include the sending dates of letters but not the receiving dates, I have to estimate the latter and the consequent waiting times to compute time-respecting paths.

70 Petrović et al. 2023, p. 2.

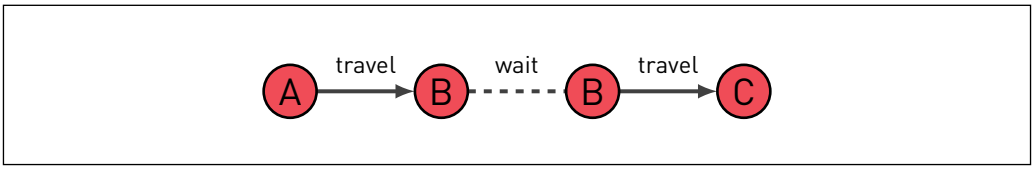


Fig. 4 Temporal information in the letter correspondence network is split into travel and waiting times. Travel time refers to the duration between the date a letter is sent and the date it is received by the intended recipient. Waiting time refers to the duration between the date a letter is received by a recipient and the date they send out a new letter as a consequence of the first one.

Constructing Temporal Networks and Time-Respecting Paths from the Letter Data

Letter correspondence data, i.e., who sent letters to whom, is popular within network analysis.[71] Merging person-specific letter editions creates a sparse superposition of ego-networks. In this network, the central figures (egos) are highly connected (hubs), while the connections between peripheral nodes are largely absent. This overrepresentation of egos necessitates degree correction in topological network measures.[72]

By accounting for edge time stamps, the aggregated network is transformed into a temporal network from which time-respecting paths can be extracted. Network analysis can reveal possible communication paths and estimate the potential of nodes to influence information transmission using topological measures. For example, centrality measures have been proposed to measure a given node's access to and control of information transmission,[73] while redundancy measures capture the resilience of information transmission to shocks like node or edge failure.[74] In this paper, I use these three categories of influence – access, resilience, control – to develop topological network measures in time-respecting paths that more accurately capture information transmission than traditional aggregated networks.

I construct a temporal network from the letter editions of the nine selected Protestant reformers using the python package pathpy.[75] Nodes correspond to reformers, edges to the exchanged letters, and edge time stamps to the letters' send-

71 Ahnert and Ahnert 2015, pp. 4–12; Ahnert and Ahnert 2019, pp. 4–12; van Vugt 2017, pp. 28–26; van Vugt 2022, pp. 120–122.
72 Ahnert and Ahnert 2019, p. 35.
73 Borgatti 2005, p. 60; Brandes et al. 2016, p. 154; Freeman 1979; p. 223.
74 Liang and Fu 2019, pp. 258–260; Jenssen and Greve 2022, pp. 58–259.
75 Scholtes 2022.

ing dates. Since pathpy requires Unix timestamps which do not cover dates before 1st January 1970, I translate the sending dates for each edge *e* into a time difference: earliest sending date – sending date of *e* [days], where the earliest sending date in the data corresponds to 1st January 1500.

I extract time-respecting paths from the temporal network with pathpy. This step requires me to specify the upper bound of inter-edge times δt, corresponding to human memory. For the letter correspondence data, δt represents the maximum time allowed to pass between the sending dates of two consecutive letters in a time-respecting path. In the case of the letter correspondences studied, δt captures the travel time of a letter plus the waiting time of the recipient between receiving the letter and sending out a new one. Since travel times varied widely in the Holy Roman Empire due to different modes of transport,[76] and reformers can be expected to wait different amounts of time between receiving and sending out a letter, estimating δt is challenging.

By the 1530s, a postal network spanned Europe, offering an alternative to letter delivery via foot travel.[77] Typical travel times within modern countries were under a week (e.g., Rome to Venice: 4–5 days), similar to foot travel durations within today's Germany, where most of the correspondences studied occurred. Given the Germany-centric focus of the data, I assume that travel times did not exceed a week for either mode of transport. Additionally, as reformers were diligent correspondents who sent letters in quick succession, I assume the waiting times also did not exceed a week, resulting in an overall estimate of δt = 15 days, or two weeks.

Despite this reasoning, I acknowledge that many journeys within the HRE likely took longer, for example due to stagecoach delays or inter-country travel (e.g., Rome to Paris: 20–25 days),[78] which is not fully captured by my choice of δt. To address this issue, I perform robustness checks to assess how a varying δt affects topological network measures (see Section 3 in Supplementary Material). The composition of the top ten ranked reformers across tested topological network measures remains relatively stable for 1 day ≤ δt ≤ 20 days, whereas it varies for larger values (30 days ≤ δt ≤ 2 years), highlighting the importance of accurately estimating or measuring travel and waiting times. I explore two approaches to estimate δt directly from the correspondence data, both of which were unsuccessful due to missing data (see Section 2 in Supplementary Material). The lower bound of inter-edge times, i.e., minimum reaction time, is set to one day, as pathpy does not allow this parameter to vary.

76 Tessier 2019, p. 333.
77 Schobesberger et al. 2016, p. 20.
78 Schobesberger et al. 2016, p. 30.

Limitations of the Path Extraction Method and the Interpretation of Paths

Extracting time-respecting paths using global parameters, like δt for maximum inter-edge time, likely oversimplifies the complex, heterogeneous structure of the Reformation. Factors like transport-dependent travel times, reformers' individual characteristics, and local political conditions varied widely, leading to different characteristic maximum inter-edge times that define the paths for the transmission of information.

Due to inaccuracies in inter-edge times, interpreting time-respecting paths as actual routes of information transmission is highly limited. To validate the extracted paths, it is essential to analyze the letter texts, extracting specific pieces of information and tracking their spread. This involves identifying distinct pieces of information within the letters and determining whether they reappear along the extracted time-respecting paths.

However, even if a piece of information reappears along a time-respecting path, it remains unclear whether it was transmitted or independently generated by the reformer. One way to distinguish these scenarios is by identifying textual clues about the source (e.g., "X wrote to me"). Nonetheless, such claims may be misleading, as individuals might falsely attribute ideas to themselves for personal gain. This highlights that validating time-respecting paths requires more than just tracking the recurrence of textual information. It is also necessary to extract contextual clues from the letters to differentiate between the transmission of existing information and the independent generation of new ideas.

Accounting for text-based context is challenging, as expressions of authorship and idea reception vary widely between letters. This requires validating inter-edge times for each letter individually, which is highly resource intensive. A practical compromise could be to analyze context clues in a subset of letters, validating only some time-respecting paths, or to use the simplified approach that tracks textual information without assessing its context. These considerations highlight the need for simplifications, even in validation. While text-based validation increases confidence in extracted paths, it does not guarantee that they were truly used for information transmission.

Given these limitations, extracted time-respecting paths should be seen as potential, not definitive, channels of information transmission. Text-based validation can help to assess whether reformers met, fell short of, or exceeded their potential influence by comparing automatically extracted path characteristics, such as length, with manually identified paths from letter texts.

Conceptualizing and Operationalizing Information Transmission

I conceptualize information transmission as the spread of divisible quantities along time-respecting paths in a letter correspondence network. The divisible quantities, i.e., pieces of information, are captured in the content of the letters, and are divisible since they can spread to different recipients simultaneously (in contrast to a person traveling, for example, who can only be at one place at a time). The potential of reformers to contribute to this transmission unfolds across three dimensions, which are taken from previous research on information transmission in networks.[79]

Access to information. To transmit information, a reformer must first access it via external information sources.[80] I assume that closer proximity to these sources improves access to information by reducing the distance it must travel, minimizing distortions.[81] I consider all nodes to be equally relevant sources that provide information via outgoing edges. I operationalize a node's potential to access information with its closeness centrality.[82] Closeness centrality *c* of node *i* is defined as the average length of the shortest path connecting node *i* with all other nodes in the network. To mitigate the selection bias in our data, giving more weight to high-degree nodes, I correct closeness by using a node's degree *d(i)*.

$$c(i) = \frac{1}{d(i)} \frac{(N-1)}{\sum_{j}^{(N-1)} s(i,j)}$$

N is the number of nodes in the network and *s(j, i)* is the length of the shortest path connecting nodes *i* and *j*. The larger the closeness of a node, the larger its potential to access information.

Resilient transmission. For successful information transmission, communication paths between source and target reformers must be resilient to external shocks, such as distortion when copying or misinterpreting information, loss of intermediary reformers (e.g., due to death or illness), or lost letters (e.g., due to transport issues).[83] I operationalize a source reformer's potential to set up resilient information transmission to a target using the number of paths, median path length, and median path redundancy, each capturing all paths between the source and target. More paths between the source and target reformer increase

79 Freeman 1979, pp. 223, 225–226; Centola and Macy 2007, pp. 709–710; Borgatti 2005, p. 60; Brandes et al. 2016, pp. 153–154; Liang and Fu 2019, pp. 258–260; Bakshy et al. 2012, p. 526; Björk and Magnusson 2009, p. 665.
80 Bakshy et al 2012, p. 526; Björk and Magnusson,2009, p. 665.
81 Freeman 1979, p. 225; Brandes et al. 2016, p. 153.
82 Freeman 1979, p. 225; Brandes et al. 2016, p. 153.
83 Morone et al. 2024, pp. 295–299.

transmission options, shorter paths reduce distortion risk, and redundant paths decrease dependence on specific intermediary nodes. The number of paths *n* between a source *i* and target *j* is defined as the number of all possible time-consecutive paths from *i* to *j*.

$$n(i,j) = |p|$$

The length of a path *p* between *i* and *j* is the number of edges $|e|$ in the path. The median path length *l(i, j)* is taken over all paths *P(i, j)* between *i* and *j*. To ensure larger values indicate a positive impact on resilient information transmission, I use the reciprocal median path length $\frac{1}{l(i,j)}$.

$$l(i,j) = median(|e| : p \in P(i,j))$$

The path redundancy of a path *p* between *i* and *j* is the proportion of nodes in *p* that are also in the longest path between *i* and *j*. The median path redundancy *r(i, j)* is computed over all paths *P(i, j)* connecting *i* and *j*.

$$r(i,j) = median\left\{ \frac{N_p \cap N_l}{|N_p|} : p \in P(i,j) \right\}$$

where $|N_p|$ denotes the number of nodes in path *p*, $|N_l|$ is the number of nodes in the longest path, and $|N_p \cap N_l|$ is the number of nodes in path *p* that are also in the longest path.

Each resilience measure is currently defined for a source-target pair. To derive individual measures for a source, I calculate the mean across all targets connected to the source via time-respecting paths. This yields the final variables of mean path count *n(i),* mean reciprocal path length *l(i),* and mean path redundancy *r(i).*

Control of transmission. Intermediary nodes lie on communication paths between a source and a target and can therefore influence information transmission by passing it on, modifying, or blocking it. Traditionally, information has been assumed to travel along the shortest paths, and that intermediary nodes become influential the more often they lie along these shortest paths, resulting in the measure of betweenness centrality.[84] Additionally, intermediary nodes can become influential the more they lie on paths that connect a source and a target node because communication between source and target must always pass via the intermediary node.

I operationalize an intermediary node's potential to influence information transmission with its betweenness centrality and the fraction of paths between a

84 Freeman 1979, p. 223; Brandes et al. 2016, p. 154.

source *i* and target *j* the intermediary node lies on, which I call the fraction of alternative paths.

The betweenness centrality b of intermediary node k is defined as

$$b(k) = \frac{1}{d(i)} \sum_{\mathrm{k}\neq\mathrm{i}\neq\mathrm{j}}^{N} |s_k(ij)|$$

where *N* is the number of nodes in the network, *d(i)* is the degree of node *i*, $|s_{ij}(k)|$ is the number of shortest paths between nodes *i* and *j* that pass through node *k*, and *k* must be neither the start nor end point of the paths in question: $k \neq i \neq j$. As with closeness, I degree-correct betweenness to mitigate the influence of high-degree nodes.

The fraction of alternative paths the intermediary node *i* lies on is defined as

$$a(k) = \frac{1}{|N|} \sum_{k\neq i\neq j}^{|N|} \frac{|p_k(i,j)|}{|P(i,j)|}$$

where $|p_k(ij)|$ is the number of paths between nodes *i* and *j* that pass through *k*, $|P(i,j)|$ is the total number of paths between *i*, and *j* and $|N|$ is the total number of node pairs in the network, excluding pairs that contain *k*.

In the following the measures defined in this section are referred to as information transmission variables and given the following simplified names: closeness, path count, path length, path redundancy, betweenness, and alternative paths. Since the measures have different units and ranges, I standardize and center them using z-score transformation to enable inter-variable comparisons in the analysis

Identifying Reformers' Potential Impact on Information Transmission

The path-based information transmission variables assess a reformer's potential to access, transmit, and control information. To determine which factors most influence a reformer's potential impact, I perform a clustering analysis of reformers on these measures. By analyzing and comparing patterns of data scores within and across clusters, I identify the key aspects contributing to a reformer's potential influence on information transmission. To avoid multicollinearity, I examine pairwise correlations among the measures and remove one measure from any pair with high correlation. This ensures that all measures are weighted equally in the clustering analysis.

I run a k-means clustering with ten random initializations of centroids per *k* on the $N \times F$ feature matrix, where *N* is the number of reformers and *F* is the number of path-based measures defined above. To determine the optimal number of

clusters k_{best}, I compute clustering solutions for up to ten clusters and use a permutation test with silhouette score as a test statistic. The silhouette score measures how similar each point is to points in its own cluster compared to points in other clusters.[85] Higher silhouette scores indicate better-defined clusters. For the permutation test, I compute a null-distribution of silhouette scores per k based on 1,000 permutations of the feature matrix and use it to compute the p-value for the observed silhouette score corresponding to this k ($\alpha = 0.05$). A detailed description of permutation tests is provided in Section 4 of the Supplementary Material.

Results

Descriptive Statistics of Temporal Network

Table 1 provides descriptive statistics of the temporal network that I constructed from the letter correspondence. The network is sparse, as the large links/nodes ratio shows. Moreover, the short average inter-event time shows that, overall, letters were written with a high frequency.

Nodes	3,348
Time-stamped links	30,043
Links/nodes ratio	8.97
Observation period	1st January 1500 – 24th June 1564[a]
Observation length	64.5 years[b]
Time stamps	10,960[c]
Avg. inter-event time	2.15 days
Min/Max inter-event time	1 day/4.12 years[d]

[a] In day-specific time differences: 0–23,550.
[b] In number of day-specific time differences: 23,550.
[c] Number of unique sending dates of letters.
[d] In day-specific time differences: 1/1,505.

Tab. 1 Descriptive statistics of the temporal letter correspondence network of reformers.

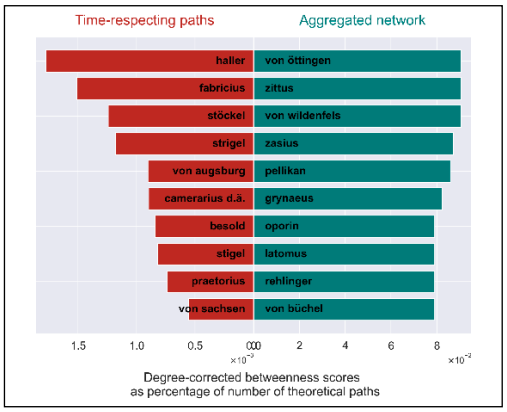
85 Rousseeuw 1987, pp. 55–59.

Confirming Biased Network Measures for Information Transmission in Aggregated Network

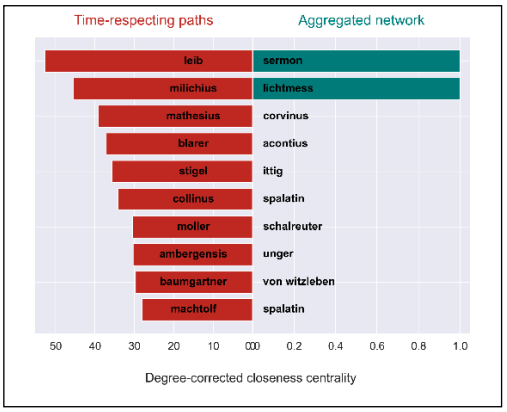
Figure 5a displays the top ten betweenness scores for the aggregated letter correspondence network and time-respecting paths. Aggregated scores are an order of magnitude larger than those based on time-respecting paths, due to the inclusion of chronologically inconsistent paths. In contrast, aggregated closeness scores are an order of magnitude smaller than those based on time-respecting paths (Fig. 5b). Specifically, except for the top two ranks, reformers have aggregated closeness scores close to zero (0.000079). These findings indicate that reformers have limited reach in the aggregated network and can more easily reach other nodes in the time-respecting paths.

For both centrality measures, different reformers rank in the top ten for time-respecting paths versus the aggregated network. This illustrates how path-based measures capture reformers' potential for information control (betweenness) and access (closeness) in ways that the aggregated approach may overlook.

Additionally, path-based centrality scores exhibit greater variance than aggregated scores, emphasizing differences in reformers' roles in information transmission, whereas aggregated scores mask these distinctions. Lastly, reformers not included in the nine selected for the analysis also appear in the top ten for both centrality measures. This is due to degree correction, which equalizes the weight given to all reformers, regardless of their number of connections. Without this adjustment, reformers with the largest degrees – those with the largest letter



(a) Betweenness. Scores for the time-respecting paths are smaller than for the aggregated network since the latter also considers shortest paths where time can run backwards.



(b) Closeness. Scores for the time-respecting paths vary more than for the aggregated network, showing that paths differentiate better between reformers' potential to access information.

Fig. 5 Degree-corrected centrality scores of the top ten reformers.

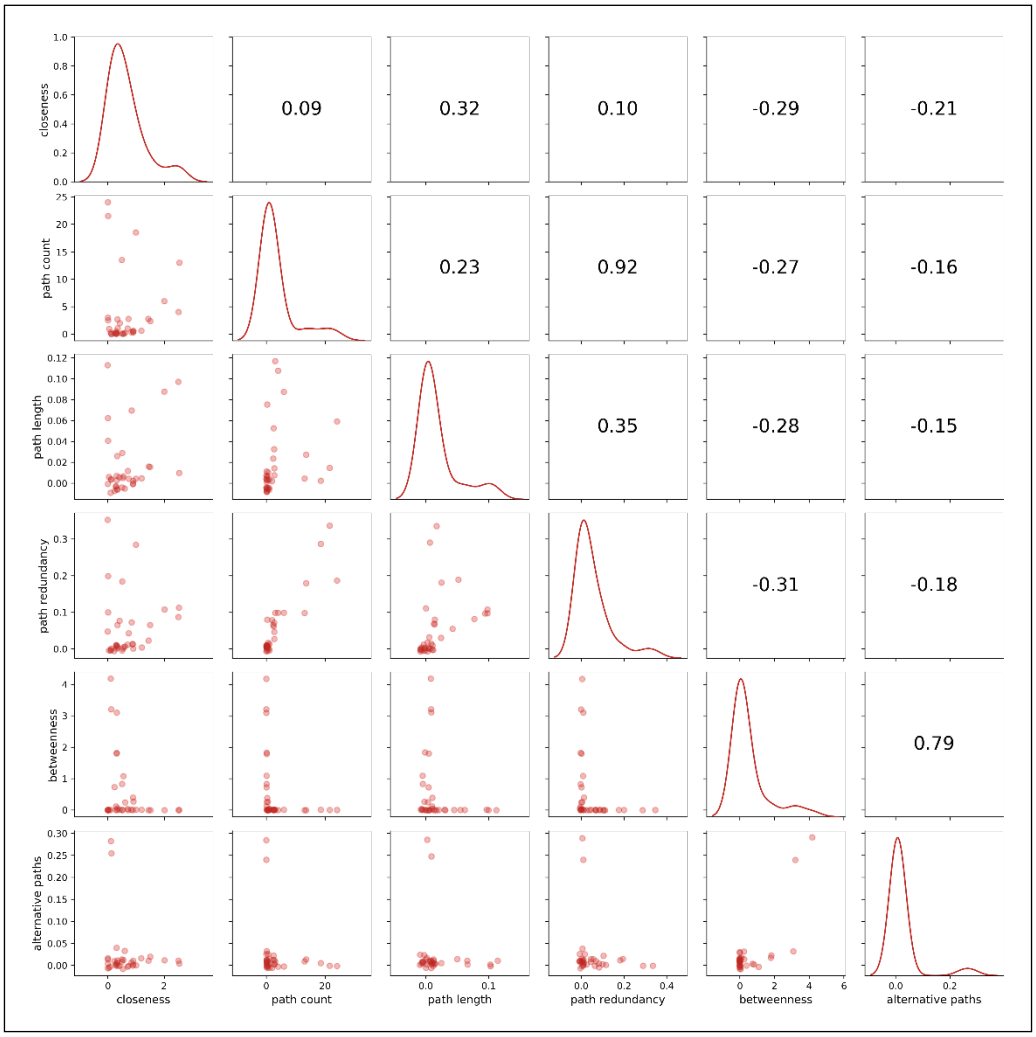


Fig. 6 Pairs plot of information transmission variables. One variable from a pair with high correlation will be removed from clustering analysis to avoid problems of multicollinearity. Diagonal: probability density functions of the variables; lower diagonal: pairwise scatter plots; upper diagonal: pairwise Pearson correlation coefficients.

editions – would dominate the rankings. This finding shows that degree-correction helped to mitigate the selection bias stemming from the restriction to nine letter editions of varying sizes.

Reformers' Potential for Information Transmission

Figure 6 shows a pairs plot of the information transmission variables. Most pairwise correlations are low, indicating that the variables capture different aspects of reformers' potential to influence information transmission. Notable exceptions include strong correlations between betweenness and alternative paths (r = 0.79) and between alternative paths and path redundancy (0.92). Whereas the scatter plot of betweenness and alternative paths is skewed by two outliers, path count and path redundancy show a consistently positive relationship. I conclude that only path count and path redundancy exhibit multicollinearity, and exclude one (path redundancy) from the cluster analysis.

The cluster analysis revealed an optimal number of $k = 3$ clusters (p = 0.003, cluster sizes: 3,329; 10; 9). Figure 7 shows heatmaps of feature scores of a random sample of reformers per cluster. By identifying color patterns within each heatmap and differences in patterns between heatmaps, I identify differences in the aspects that drive reformers' potential to influence information transmission.

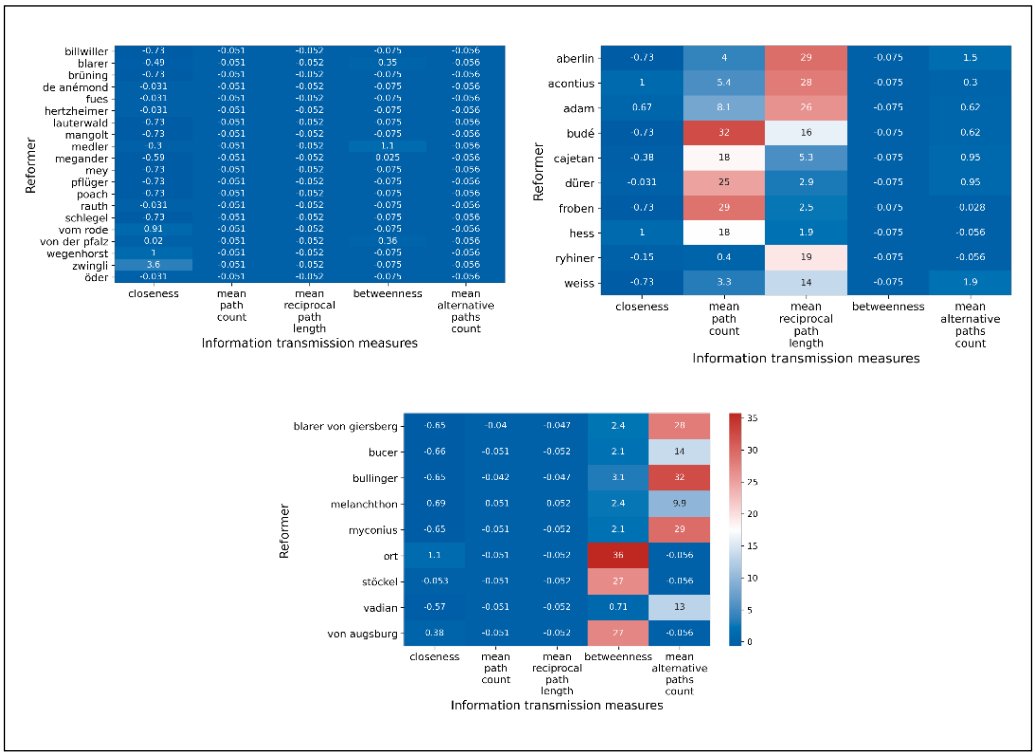


Fig. 7 kmeans clustering result for $k_{best} = 3$. Heatmaps visualize clusters, showing the scores on the information transmission variables for a random subsample of reformers.

Cluster 1 is characterized by scores at the low end of the value spectrum across all features (Fig. 7a). This indicates that this group of reformers does not have a strong potential to affect information transmission via any of the proposed dimensions of access, resilience and control. Since this cluster includes over 3,000 reformers, identifying overarching commonalities is challenging. Therefore, I focus on the nine selected reformers whose letter editions form the basis of this dataset. Among them, Martin Luther (Lutheran), Andreas Karlstadt (Radical), Huldrych Zwingli (Swiss Reformed), and Johannes Oekolampad (Swiss Reformed) are part of cluster 1. They stand out for their denominational rigidity – each firmly supported a single Protestant tradition and rejected efforts to reconcile different denominations. Additionally, all four belong to the first generation of the Reformation, having been born before 1500.

Cluster 2 is characterized by above-average path count and path length (Fig. 7b). Reformers in this group create numerous short, time-respecting paths, enhancing resilient information transmission. Low scores for the remaining features indicate limited opportunities to gain access to information and control transmission between others. As a result, their potential to influence information transmission is moderate, driven primarily by their ability to start resilient paths.

Reformers in cluster 2 are marked by pluralism in terms of both their professional background and denominational belief. They include diplomats (Jacobus Acontius: secretary to a cardinal in Milan; Guillaume Budé: French ambassador to Rome; Johannes Hess: secretary to the Bishop of Breslau; Thomas Cajetan: papal legate), artists (Albrecht Dürer: painter; Joachim Aberlin: wrote a version of the Bible in rhyming form), merchants (Hieronymus Froben: printer), and lay reformers (Aberlin: teacher; Adam Weiss: pastor). This group supports different Protestant denominations: Calvinism (Budé), Lutheranism (Dürer, Hess, Weiss), Swiss-Reformed (Aberlin, Acontius), and Catholicism (Cajetan). Their approaches to denominational aims also vary. Some took a diplomatic approach, attempting to reconcile Protestant denominations (Acontius, Hess, Weiss), while others avoided active theological debates (Aberlin, Budé, Dürer, Froben), and some engaged fanatically in defending their own beliefs (Cajetan). Thus, while reformers in both clusters 1 and 2 support different denominations, cluster 2 is distinguished by its more diverse professional backgrounds and a range of approaches to how reformers engage with their faith.

In cluster 3, betweenness and alternative path score above average (Fig. 7c). Reformers in this group create opportunities to control information transmission by acting as intermediaries on many of the shortest and alternative paths. Low scores on other features indicate limited opportunities for influence through other means. Like cluster 2, reformers have a moderate potential to affect information transmission, but in cluster 3 it is driven by their control over existing communication paths.

Reformers in cluster 3 share a scholarly background and were actively engaged in efforts toward Protestant unity. This includes theologians who shaped the doctrinal foundations of Protestantism, such as Bucer (Confessio Tetrapolitana); Melanchthon (Confessio Augustana and Variata); Stöckel (Pentapolitana); Bullinger, Myconius, Bucer (First Helvetic Confession); and Blarer (signed Tetrapolitana for Konstanz). These reformers sought a consensus between the Lutheran and Swiss branches of Protestantism. Exceptions include Joachim Vadian (physician) and Otto von Augsburg (bishop). Although not theological scholars, both were involved in efforts related to denominational reconciliation – Vadian maintained contacts with moderate reformers, while Otto opposed unity efforts, reflecting a desire to control communication to prevent consensus. While cluster 2 is characterized by a pluralistic professional background and varying denominational approaches, cluster 3 stands out for its more homogeneous makeup, with theological scholars focused on unifying Protestant denominations.

The superposition of ego-networks might suggest that the clustering results are merely a product of the network's topology, especially given the uneven cluster sizes. While topology likely plays a role, this concern is alleviated by the following findings: instead of forming nine separate clusters for each ego reformer, the optimal solution identified only three clusters. Ego reformers and peripheral reformers were not divided into separate clusters, nor were ego reformers grouped exclusively with their peripheral nodes. The results do not suggest a straightforward bias driven by the network topology, but comparative studies with varying network topologies are needed to investigate this in more detail.

In summary, the clustering analysis revealed three clusters of reformers along five features, capturing potential ways of how reformers could have influenced information transmission via letters. Cluster 1 contains reformers who score low on all features indicating a low potential to influence information transmission. Reformers in clusters 2 and 3 score high on resilience-based and control-based measures, respectively, indicating that their potential to influence information transmission is built around one method.

Discussion

This article analyses the potential for information transmission during the Protestant Reformation via letter correspondences based on the collections of nine prominent Protestant reformers, including Luther, Melanchthon, Zwingli, Bullinger, Karlstadt, Myconius, Bucer, Oekolampad, and Vadian. The aim is to identify the driving factors of reformers' potential influence on information transmission.

I apply a path-based temporal network approach that was hitherto under explored for historical data. Based on a letter correspondence network of reformers, I use the sending dates of letters as edge time stamps to extract time-respecting

paths. Time-respecting paths are sequences of nodes connected by chronologically ordered edges with bounded inter-edge times.[86] Temporal ordering is crucial to ensure that information only spreads forward in time. This property is not preserved in aggregated networks where information is allowed to spread backwards in time, potentially leading to biased topological network measures.[87]

I use path-based topological network measures to operationalize reformers' influence on information transmission and cluster reformers along these measures to reveal factors that drive reformers' potential to influence that transmission. The results revealed three groups of reformers: one with low potential to influence information transmissions; one with medium potential driven by the establishment of resilient communication paths that protect the transmission of a message from shocks, such as the death of an intermediary correspondent; and one with medium potential driven by the control of existing communication paths between other reformers. These results suggest that a reformer's potential, if present, is shaped by a specific factor, which can vary between reformers. Interestingly, access to information did not drive the potential of any reformer in the data.

Reformers with medium potential to transmit information either have diverse professional backgrounds (e.g., diplomat, artist, merchant) and use diverse denominational strategies (e.g., avoid theological debates, reconcile Protestant denominations, defend their denomination fanatically) (cluster 2), or come from a theological scholarly background and support reconciling different Protestant denominations (cluster 3).

For reformers in cluster 2, their ability to create resilient communication paths suits their diverse professional backgrounds and strategies, enabling them to engage with a broad range of recipients and create multiple communication routes. In contrast, reformers in cluster 3 rely on controlling existing communication channels. As established theologians, they are likely well-embedded in intellectual networks, which enables them to influence information transmission more effectively than if they were less well connected.

This analysis has limitations. With data from only a few letter editions, the network is sparse, likely missing many communication paths and capturing only a subset of possible information transmissions. More concerningly, the extracted paths may be incorrect due to disambiguation errors, missing data, and oversimplified global path parameters.

86 Pfitzner et al. 2013, p. 1; Holme and Saramäki 2012, p. 3.
87 Scholtes et al. 2016, pp. 1–2.

While I accepted inaccuracies in disambiguation and missing values for pragmatic reasons (semi-automatic disambiguation is quick, and I received digitized data rather than digitizing it myself), I mitigated bias in the network structure and the choice of parameters through degree-corrected measures and robustness checks on the maximum inter-edge time. Although these robustness checks showed that network measures remained relatively stable up to $\delta t = 20$ days, they do not account for individual-level differences in maximum inter-edge times among reformers and context conditions (see Section 3 in Supplementary Material). Some modeling approaches for node-specific time scales already exist,[88] but they require tuning for historical data due to data sparseness, which can cause error measures to collapse.

The key question is to what extent time-respecting paths reflect real-world communication channels through which reformers spread information in the 16th century. Although time-respecting paths capture a necessary condition for information transmission – an incoming edge has to precede an outgoing one – they are not sufficient for this purpose. In practice, not every time-respecting path has to be used for information transmission, since correspondents can relay different information from what they received in a previous letter. This is why I model reformers' potential to influence information transmission, rather than their actual influence.

Validating whether time-respecting paths correspond to real-world communication channels requires analyzing the letter texts. Information would need to be extracted, its origin checked – whether reformers passed on existing information or generated new content – and its passage tracked along the time-respecting paths, based on formulations in the texts. Additionally, this text-based validation could reveal whether reformers meet, fall short of, or exceed their potential to influence information transmission. For example, if a reformer in cluster 2 (focused on resilient transmission paths) fails to transmit information via short, redundant paths, they would underperform. Conversely, if a cluster 1 reformer (with low potential) succeeds, they would exceed expectations. Such findings would shed light on how individuals leverage or overcome the constraints of their network positions.

In summary, this analysis used time-respecting paths to incorporate temporal information in historical networks. This approach addresses the problem of achronological information transmission present in aggregated networks and temporal network snapshots. The time-respecting paths helped identify key factors behind the reformers' potential to influence information transmission. It distinguished reformers with low potential from those with medium poten-

88 Petrović et al. 2023, pp. 3–5.

tial, who either established resilient communication paths or controlled existing ones. This study contributes to the important question of accounting for time in historical data analysis.

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