Prices of peers: identifying endogenous price effects in the housing market.

Short title: "Endogenous price effects in the housing market."

by Nikodem Szumilo[1]

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Abstract: *The paper identifies neighbourhood price spillovers in the housing market. Although this concept attracted some theoretical research and is strongly supported by practitioners, it has proven very difficult to show in empirical data. By using the linear-in-means model, which is routinely applied to identify endogenous effects in groups of peers, the study summarizes all threats to identification and demonstrates how they can be addressed by exploiting information asymmetry between buyers of different houses and delays in revealing transaction prices. The results show that a 1% increase in the price of a house increases its neighbour's price by up to 0.3%.*

Keywords: peer effects, house prices, price spillovers, price multiplier

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[1] Nikodem Szumilo is at the UCL – University College, London, UK. Email: n.szumilo@ucl.ac.uk.

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1. Introduction

In the housing market a large proportion of the correlation between asset prices is not explained by models based purely on economic fundamentals. For example, although autocorrelation and momentum effects are well documented (Case & Shiller, 1989), there is no consensus on what process drives these phenomena. In addition, despite strong evidence of spatial correlation in prices, no consistent theoretical framework appears to be able to fully explain it (LeSage & Pace, 2009). While housing researchers have a long tradition of adjusting for these phenomena using econometric techniques, these approaches do not capture the causes of correlations between house prices (Overman & Gibbons 2012). In financial markets, similar patterns are explained by theories that assume that prices of different assets are endogenously correlated. Such interactions between prices are a well-established notion which derives its theoretical foundations from information frictions (Veldkamp 2006). Research argues that it leads to endogenous trends in prices as well as to propagation of shocks across time and industries (Hong and Stein, 1999). If it exists in the housing market, an endogenous price effect could explain similar patterns that occur in house prices (Case and Shiller 1989, Simonshon and Loewenstein 2006, Glaeser and Nathanson 2015). For example, like it does in social interactions (Manski 2001), it could create a 'multiplier effect', and cause average house prices in a neighbourhood to 'overreact' to changes in values of the area's fundamental characteristics (Glaeser et al. 2003, Brunnermeier 2001). This would have significant implications for policy makers concerned with the housing market and challenge some assumptions of popular policy evaluation methods. In this paper, I apply a novel identification approach and demonstrate that prices of buildings located next to each other affect each other directly.

The key innovation of the current study in the context of the asset pricing literature is to use the linear-in-means (LIM) model to present the price of a house as a function of its own characteristics as well as of characteristics of its neighbours. The benefit of this approach is that challenges to identification can be isolated and resolved by following the rich literature on identifying peer effects in social interactions where the LIM model is evaluated in great detail.

The practical challenge is to disentangle the interactions between prices of adjacent buildings from their common determinants. I start by defining 'fundamental' price determinants as all (observable and unobservable) features of a house that affect its price but are neither its own (historical) price nor the price of surrounding properties. To achieve identification, I separate neighbourhood spillovers of prices from changes in area fundamentals by focusing on internal renovations which change the quality of the renovating houses but do not affect the fundamental characteristics of the area or of nearby properties. In this, I exploit the information asymmetry between buyers of renovated properties (who pay a premium for a higher quality asset) and subsequent buyers of houses in the same area (who can observe transaction prices but not the internal quality of properties transacted in the past). This allows me to observe how prices of buildings change when their own fundamental characteristics remain constant but prices of their neighbours change. To control for unobserved changes in area quality (for example renovated houses attracting buyers that have a positive impact on the value of the neighbourhood), I exploit the unique structure of the house price disclosure system in England. As all transaction prices were released with a delay of around three months after the transaction takes place[2], properties sold at the same time will be exposed to the same neighbourhood effects but cannot infer information from each other's prices. I demonstrate that premia for internal renovations only affect neighbourhood prices after the price of the renovated property is made public.

Although several theories explain why prices may be endogenously correlated (for a summary see Bursztyn et al. 2014), little robust evidence exists to support any of them. In fact, providing empirical support for specific models may simply be impossible as prices are determined by highly complex processes in which individual factors often cannot be identified (Manski 2000, Bursztyn et al. 2014). I

[2] The date of the transaction is the date at which the property legally changes ownership and usually corresponds closely to the date at which the new owners moves in.

therefore focus on identifying the price spillover rather than any one process that drives it. However, to motivate the empirical approach, I discuss two of the most widely advocated reasons for buyers to be influenced by prices of other assets: 1) buyers use prices in the area to learn about the value of the house they are buying (Veldkamp 2006) and 2) the discount rates buyers apply are affected by discount rates they observe (Bursztyn et al 2014).

The study uses a sample of repeat sales transactions of almost 27,000 terraced houses in London over a period of ten years and tracks their renovations. By controlling for changes in the quality of the properties using a repeat sales approach, it is possible to show the impact of the change in a dwelling's characteristics on its own price and (through the average price in the neighbourhood) on prices of other properties. This allows me to demonstrate that, house prices are affected by average prices in the neighbourhood even when the driver of the average price is unrelated to the fundamental value of other properties. To further reinforce the claim, I distinguish between internal renovations and ones that can be observed from the outside to show the different impacts they have on prices of the renovating properties and of their neighbours. The study shows that both types of renovations affect prices of their neighbours but that only internal renovations do so through average prices in the neighbourhood. The key identifying assumption is that internal renovations do not affect other properties in any way other than through the price of the renovated house.

To validate the results in a sample where renovations are exogenous, I instrument them with renovations that occur after accidental fires. Specifically, I use small accidental fires that affect a single room and require minor refurbishments, cannot be seen from the outside and are not distinguishable from other renovations. To my knowledge this is the first study to uniquely identify the impact of a change in the price of one asset on the price of another. I call this endogenous interaction the peer-price effect.

The first significant finding is that internally renovated houses have prices higher by around 5%. The results also show that an internal renovation of a sold house increases the price of the nearest neighbour by around 2% but the effect is zero until the transaction price of the renovated house is made public. This means that house prices are strongly influenced by information contained in average price of their neighbourhood. Two stage least square (2SLS) estimation results using small accidental fires to instrument for internal renovations confirm that after the price of a property is induced by an internal renovation, the price of its neighbour is affected only through the price channel and not trough changes in any common fundamental characteristics. Although the sample for these tests is small, the results are very similar to earlier estimates and show a strong positive influence of internally renovating a property not only on its own price but also on prices of its neighbours. In addition, minor fires have no impact on prices in the neighbourhood at the time of the incident and they affect them only after the building affected by a fire is sold. This supports the claim that the transmission mechanism relies on prices. Ancillary results demonstrate that there is no evidence that internal renovations affect other properties in any way other than through prices. The study also discusses the implications of the endogenous price effect. It shows that, as predicted by spatial and social models of endogenous interactions, a 'multiplier effect' may magnify the impact of exogenous neighbourhood changes on house prices by as much as one third.

This study makes an important contribution to the growing literature on endogenous interactions between prices of assets related to each other by providing a robust identification framework. It is notoriously difficult to construct strong identification strategies for peer-induced effects as data is limited and numerous important factors are unobservable (Manski 1993). Usually, it is only possible to observe a correlation between characteristics of group membership and an outcome. For example, Folcault and Fresard (2012) show that corporate investment decisions are correlated with stock prices of their peers and argue that this shows that managers learn new information from prices of stocks of other firms. While their findings show a robust correlation they are not able to disentangle the price signal from other determinants of investment levels. Some initial evidence of spill over effects between prices of stocks is provided by Honkanen and Schmidt (2017) who show that when a change in the price of a stock is induced by a mutual fund fire sale, prices of its economic peers are also affected. However, while their study provides interesting insights, their empirical strategy does not distinguish between the effect on the fundamental characteristics of the group and the effect on share prices in the group which means that the peer-price effect cannot be quantified.

The present study also contributes to the literature on neighbourhood effects in the housing market. In this field the use of the LIM model is less innovative as social interactions are a common topic of interest in neighbourhood research (Ioannides 2011). However, achieving identification of peer-price effects remains an unresolved challenge and while many modern studies of house prices attempt to isolate exogenous factors from individual and correlated effects, the possibility of an endogenous peer-price effect receives little attention. The closest to the present study is the research by Harding et al. (2009) and Gerardi et al. (2015) who evaluate the spatial impact of foreclosures on prices of houses in the neighbourhood. Although most studies of this issue report very statistically significant spatial effects of foreclosures, they usually cannot control for possible relationships between individual, exogenous and correlated effects that may be affecting prices in locations where foreclosures occur. This makes isolating the effect of a house going through a foreclosure process on prices in its neighbourhood difficult.

The paper proceeds as follows: Section 2 discusses the concept of house prices in the context of group effects; Section 3 describes the empirical strategy of identifying the peer-price effect; Section 4 presents the data; Section 5 presents and discusses empirical results and section 6 concludes by offering final remarks.

2. House prices in a neighbourhood

Most modern studies of house prices recognize that housing is a composite good and use the framework presented by Rosen (1974) to represent its price as a vector of asset-specific characteristics and their market-determined shadow prices. The basic assumption of Rosen's hedonic model is that characteristics are observed while their corresponding shadow prices can be determined by matching transaction prices with differentiated bundles of specific attributes. In this set up, the obvious reason for prices to be correlated across assets is due to their correlated characteristics. Since house prices are partially determined by characteristics of the area they are located in, prices in the same neighbourhood should be correlated to each other through the characteristics they share.

While here it is clear that location features may be a significant driver of cross-asset price correlation, houses located in the same area very often also share many building-specific features such as size, design or age. Since correlations of these unique features are difficult to measure, historically studies of cross-asset correlations were often limited by data availability issues. As more data becomes available but prices are still found to be correlated across space, empirical research suggests that this effect cannot be explained by known observable features. One explanation of this phenomenon is that prices are simply driven by characterises that are observable to buyers and sellers but not to econometricians. Another, more controversial, hypothesis is that prices are endogenously affecting each other and average house prices in the neighbourhood (P_n) provide additional information used to estimate prices. I represent this problem using the standard simplified form of the linear-in-means (LIM) model of peer effects in social interactions (Manski 1993, Blume et al. 2015):

$$[\mathbf{1}]\ P_i = \delta + \beta x_i + \rho P_n + \alpha X_n + \varepsilon_i$$

Where P is price, x is a vector of unique characteristics of property *i*, X is a vector of characteristics typical for houses in neighbourhood *n,* δ is a constant and ε in an error term. Here, the endogenous price interaction may be formally defined as an expectation that the price of a house in a neighbourhood will be equal to average prices in that location: $E(P_i|i \in n) = P_n$. At the same time, the effect that occurs through common characteristics is defined simply as the expected unique characteristics of a house in a neighbourhood being the same as the shared neighbourhood characteristics and equal to the average unique features of houses in the area $E(x_i|i \in n) = X_n = \overline{x}_n$ (where $\overline{x}$ is the average of characteristics x).

Theoretical rationale

The above equation intentionally specified a very general empirical model that lends itself to a number of different theoretical approaches to endogenous price interactions presented in the literature over the last fifty years. While it is not possible to support any specific theory using the data available in this paper, below I review the most popular ones to rationalize equation 1.

The original idea of rational reasons for price-on-price interactions comes from the pioneering work of Shiller (1981) as well as Pindyck and Rotemberg (1993) who demonstrate that prices of financial assets move together to a larger extent than predicted by traditional economic fundamentals. Although different rational theoretical explanations of this empirical finding have been offered by the literature, many suggested that prices of assets could endogenously affect each other. For example, portfolio rebalancing (Kodres and Pritsker, 2002), wealth (Kyle and Xiong, 2001) or liquidity constraints (Calvo, 2004) effects could explain why the change in the price of one asset affects the price of another. However, these effects would lead to relatively small price effects and the most popular explanations of large endogenous price interactions focuses on two areas 1) learning from prices of other assets due to imperfect information and 2) anchoring effects.

<u>Learning from prices of other assets:</u> This literature points out that it is difficult to accurately estimate the value of the flow of services[3] offered by an asset when information is imperfect. In this scenario prices of assets may include information that is otherwise unobservable. Therefore,

[3] While different complex definitions can be used (for examples see Grossman and Laroque 1990) the easiest way to conceptualize this is to think of expected rents for housing and dividends for stocks.

interpreting changes in prices of some assets may offer information that helps better understand the fundamental value of other assets. Indeed, Fox et al. (2003) use an exogenous shock caused by a legal reform to demonstrate that information availability seems to be a key driver of the comovement of asset prices. Wadhwani (1990) builds a theoretical model with informed and uniformed investors and shows that the latter have an incentive to try to infer the fundamental value of assets from their prices. Critically, this is true even if the cost of doing so is the probability of misinterpreting the signal and making a valuation mistake. In addition, there are forms of information asymmetry under which learning from prices of other assets can also benefit sophisticated investors. For example, when more information is observed for a group of assets than for any single asset, an information pooling process would result in endogenous price interactions (Shiller 1989). More recent theoretical models include the work of Veldkamp (2006) who considers a signal about many assets observed by many investors in a world with restricted information on individual assets. She shows that in this scenario, the prices of assets grouped in the same basket will endogenously affect each other as investors will infer the value of individual assets from the value of the group. This study can be easily conceptualized in the context of the housing market. Indeed, Ioannides and Zabel (2008) give the possible signal contained in neighbourhood prices a very specific form by suggesting that it might reflect the otherwise unobserved characteristics of its residents. They model the location choice of a household and make it conditional on the perception of the characteristics of current and future residents of an area. Their model separates housing demand into demand for structures and demand for neighbourhoods. This allows them to show that when sorting into neighbourhoods based on preferences is allowed, a household's demand for housing structure depends on their neighbours' demand. Indeed, the empirical strategy adopted in their paper demonstrates endogenous interactions of housing demand within US census tracts and a social multiplier effect.

Anchoring: A different mechanism leading to the peer-price effect comes from behavioural economics and argues that humans may change the discount rates used to convert the flow of services of an asset into its price. This literature argues that the reason for prices to move together might be the fact that humans tend to anchor their beliefs to reference points (Northcraft and Neale 1987, Beggs and Graddy 2009). Indeed, Bursztyn et al. (2014) show that discount rates of individuals can be affected by discount rates they observe. If two prices are anchored to the same reference point, their prices may be correlated but this does not necessarily imply peer price effects (Foerster & Karolyi 1999). However, if the price of a group is the reference point, it will endogenously influence the discount rates of individuals anchored to it. In the housing market this is documented by Simonshon and Loewenstein (2006) as well as Lambson et al. (2004) who show that buyers (conditional on their characteristics) who move from more expensive markets are willing to pay higher prices. Glaeser and Nathanson (2015) build on this concept and present a model in which households make extrapolative predictions about future house prices based on their historical values. Indeed, there is also research showing anchoring biases in valuations of commercial properties performed by expert surveyors (Clayton et al. 2001). There is also evidence that these effects are propagated through social networks within neighbourhoods. Patacchini and Venanzoni (2014) model hosing demand within social networks. Specifically, they model demand for housing quality as a function of the demand of other agents in the same network. They find support for their model in empirical data of US students who are best friends within census tracts. Importantly, they document the effect only in already existing social networks so the implication for the endogenous price effect would be through actions of the sellers. For example, sellers could be under pressure from their social network to achieve a sale price close to a recent transaction price of their neighbours.

The model in equation 1 is also very similar to many popular spatial models but assumes no decay of spatial effects with distance. The average of individual characteristics in the area X can be interpreted as the equivalent of a spatial lag of characteristics of neighbours. At the same time the average price in the neighbourhood can be interpreted as the spatial lag of prices of nearby properties. This shows how the LIM specification is similar to the spatial Durbin model (Elhorst

2014). The main advantage of using the LIM model rather than the Durbin model is the fact that the former is supported by a rich body of literature on identifying the endogenous effect between outcomes of individuals in a group. Importantly, Manski (1993) shows that identifying assumptions of the LIM model hold even in non-parametric specifications. Indeed, Gibbons and Overman (2012) note that functional form is paramount to identification of the direct interactions between house prices in a neighbourhood.

Naturally, ρ of equation 1 can only be fully interpreted in the context of the mechanism that drives it. While this paper is unable to support any one mechanism, I demonstrate that both learning and anchoring can be easily mapped to equation 1. Below I derive empirical specifications for the two mechanisms.

Possible mechanism 1: Learning about area effects from prices of other assets.

In a world with perfect information and a group of identical houses, all prices equal the average price and are determined by the average characteristics and their shadow prices ($P_i = \alpha x_n = P_n = \alpha \bar{x}_n$). In a world with perfect information but houses with random deviations from the average, prices depend on own unique characteristics and on characteristics of other buildings. However, each building's characteristics (x) can be broken down into ones that affect only itself (s) and ones that affect itself as well as other houses in the area (k). Since only k characteristics affect other buildings, the average of k in the area (denoted with a dash) can be represented as the area effect ($P_i = \beta x_i + \alpha \bar{k}_n$). With information frictions, some components of k are observable to buyers of property i as well as to buyers of other buildings (k_{io}) while others are unobservable to the public and only the resident knows them (k_{iu}). Area averages of both are important for prices of individual buildings:

$$P_i = \beta x_i + \alpha(\bar{k}_{no} + \bar{k}_{nu})$$

In order to accurately price a house in n, the information on $\bar{k}_{nu}$ is required but, since it is unobservable, is not available. However, information on prices of other buildings is easy to access. Average prices in the area are formed by averaging values of own characteristics of houses sold in the area and values of observable as well as unobservable features of other buildings in the area ($P_n = \beta(\overline{s}_{\mathrm{n}} + \overline{k}_{\mathrm{n}}) + \alpha(\overline{k}_{no} + \overline{k}_{nu})$). This expression can be solved[4] for $\overline{k}_{nu}$ and gives:

$$\overline{k}_{nu} = \frac{P_n - \beta\overline{s}}{\beta + \alpha} - \overline{k}_{no}$$

Substituting this into the equation for the price of property i gives:

$$[2] \quad P_i = \beta x_i - \frac{\alpha\beta}{\alpha + \beta}\overline{s}_n + \frac{\alpha}{\alpha + \beta}P_n$$

This represents the price of property i as a function of its own characteristics, the price in the neighbourhood and of the average of characteristics that affect only the value of the buildings they are specific to. This maps easily to equation 1[5]. Note that this assumes that information asymmetry only occurs for characteristics that affect other houses $\overline{k}$, while features that only affect own price $\overline{s}$ are observable to all (or do not exist). If that is the case, prices can be accurately estimated even under information asymmetry and the price of i does not change.

However, if $\overline{s}$ is unobservable and different from zero, using prices in the area to calculate the value of their unobserved characteristics for property i, would introduce a bias. Note that this bias would also affect other transactions through the impact it has on the average price in the area[6]. Therefore, if $\overline{s}$ influences prices of other buildings, prices are different then they would be with perfect information.

[4] Note that $\overline{k}_{no} + \overline{k}_{nu} = \overline{k}_{\mathrm{n}}$.

[5] Note that for simplicity of exposition correlated effects that affect characteristics of all houses simultaneously are ignored.

[6] In a dynamic setting, the bias would affect the area average price and therefore the subsequent transaction. Further transactions would be affected by the bias of all former transactions compounded into the average price.

Possible mechanism 2: Benchmarking (learning about discount rates).

Suppose that information is freely available but the value of each characteristic of a house is anchored to the value of the same characteristic in surrounding houses. In isolation (denoted as iso), the price of a property is set by the shadow prices of its own characteristics and characteristics of its neighbourhood ($P_i^{iso} = \beta_i x_i + \alpha_i X_n$). If other (identical[7]) houses in the area priced these characteristics differently ($P_n - P_i^{iso} = \beta_a \bar{x}_n + \alpha_a X_n$), anchoring causes the shadow prices to be affected by the difference (denoted as *a*) with a parameter w ($P_i = P_i^{iso} + \mathrm{w}(P_n - P_i^{iso})$). Substituting the difference between the price in the neighbourhood and the price in isolation into this equation leads to the familiar specification similar to equation 1 but with $w = \rho$:

$$[3]\ P_i = (1-w)\beta_i x_i + (1-w)\alpha_i X_n + wP_n$$

Here, the price of i is given by weighting the average price in the area and the price of property i in isolation by parameter w. This also maps directly to equation 1. Assuming that all houses are identically priced in isolation, an exogenous one unit change in characteristics of houses (or the neighbourhood) would be split between the independent valuation and the anchoring component. This would result in the same impact on price as in the absence of the anchoring component so there is no mispricing.

A problem may arise when houses and preferences are heterogeneous across space and/or individuals. In this case, seemingly identical houses could be priced differently in isolation. Indeed, this is especially problematic if information is imperfect. Consider for example a change that affects only the residents of a house (type s). This influences its price but should not affect prices of other properties. However, with imperfect information it is difficult to distinguish between changes of type s and of type k_{iu} (unobservable changes that affect all properties in the area). In this case buyers of other buildings do not know if the change in price is caused by a change in characteristics or by a

[7] Because houses are identical $x_i = \bar{x}_n$.

change in the discount rate applied to unaltered characteristics. This may lead to endogenous price interactions.

The cost of information and real estate market practice.

In practice, collecting and processing information on characteristics of other buildings is costly while data on prices is easily available. When estimating their reservation prices buyers and sellers face a choice: paying for information or accept the risk of a bias coming from using prices in the area. As concluded by Salop and Stigliz (1977), higher information acquisition costs encourage buyers to infer information from prices of sold assets. This is consistent with the common theoretical claim that in markets with greater information asymmetry price signals have more influence on subsequent transactions (Banerjee & Green 2015).

This does not imply that buyers and/or sellers are irrational. On the contrary, they choose to accept the risk of transacting a house at a price distorted (upwards or downwards) only as long as this cost is lower than the cost of estimating shadow prices of all neighbourhood characteristics in any other way. Therefore, the peer-price effect should be affected by providing cheaper information about neighbourhood characteristics or by decreasing the risk of the average price in the neighbourhood being a source of noisy information[8].

Paradoxically, these issues are reinforced (rather than mitigated) by real estate market professionals. Buyers and sellers often turn to experts and ask for valuations. However, surveyors focus on predicting transaction prices (rather than the value of a property to buyers or sellers) and use methodologies that are guided by empirical correlations. This means that they are usually biased towards recent transactions in the neighbourhood (RICS 2003). Although recently automated valuation models begun to replace human experts, their algorithms are often based on the same empirical models. This means that spatial autocorrelation of prices is encoded as a structural feature of the market and that predictions of those models generate results that reflect this assumption.

[8] In the appendix (section 6), I show that in places where the latter is true due to a larger number of transactions, the peer effect is weaker.

This market structure may reinforce the impact of the peer-effect on house prices as a self-fulfilling prophecy (DeCanio 1979).

While the empirical approach employed below is unable to suggest if the peer-price effect is caused by learning from values of other asset, anchoring, a combination of these two effects or a completely different mechanism, it provides a credible estimate of ρ.

3. Estimation and identification strategy

Although identifying peer effects is notoriously difficult, it is sometimes possible to exploit fixed effects across entities (Lavy et al. 2012) or time (Arcidiacono & Nicholson 2005), the direction of interactions between peers (Bramoullé et al. 2009), unique features of market structure (Brown et al. 2008) or information asymmetries (Manski 2000). The present study applies a combination of the last two strategies and uses the structure of the English housing market to exploit informational asymmetries between parties to a transaction (buyers and sellers) who observe all characteristics of the transacted house (private and public information) and outside observers who only observe selected characteristics (public information). In this framework, prices, neighbourhood amenities and the external quality of a house are public characteristics while its internal quality is private. In this setting, all changes to internal quality are private, while all changes to other determinants of house prices are public. At this stage, it makes no difference if the internal quality affects other houses directly or not. The identifying assumption is that an internal renovation is not observable to buyers of other houses directly and therefore it can only affect them when the price is revealed. This is sufficient to identify a process of prices interacting with each other directly but it does not show if the interaction is driven by perfect learning from prices of other assets or by an endogenous price-to-price interaction. To address this issue, I assume that internal renovations do not affect the value of other buildings in any way other than through the price of the renovated building. I later demonstrate that both identifying assumptions are supported by data.

These assumptions make equation 1 suitable for the standard solution to the linear-in-means model in a group with characteristics that vary from the mean (Blume et al. 2015). This approach represents the price of each house as a function of its own private characteristics, public characteristics of the area and private characteristics of other houses sold in the area. I start by introducing a time dimension denoted by t to indicate the time of sales of a house into equation 1:

$$[\mathbf{4}]\ P_{it} = \beta x_{it} + \rho P_{nt} + \alpha X_{nt} + \varepsilon_{it}$$

I also define the price in the neighbourhood as the average transaction price of houses sold in the area*:*

$$[\mathbf{5}]\ P_{nt} = \frac{\sum_{j=1}^{N} P_j}{N}$$

Where N is the number of transactions in the neighbourhood that occurred in neighbourhood n before time t. The next step is first-differencing so that each variable becomes a change between the first and the second transaction of house i, all time-invariant variables drop out and the subscript t now denotes the time of the second transaction. Solving equations 4 and 5 for the price of i gives (see appendix A for proof):

$$[\mathbf{6}]\ \Delta P_{it} = \beta \Delta x_{it} + \alpha(1 + \frac{\rho}{1-\rho})\Delta X_{nt} + \frac{\beta\rho}{(1-\rho)} \frac{\sum_{j=1}^{N} \Delta x_j}{N} + \Delta\varepsilon_{it}$$

As explained earlier, average prices in the neighbourhood incorporate the characteristics of houses that are not observable (or costly to observe) to anyone apart from their buyers and sellers. Therefore, the endogenous peer price effect can be identified, if prices in the neighbourhood are driven separately by changes in house characteristics that are unobservable to the neighbourhood (private) and observable changes (public).

I focus on a special case of equation 6 in which changes to individual quality are of type s (affect only the occupiers) and are subject to information frictions (only the occupiers know about them). Therefore, when the average price in the area is affected by the renovated property revealing its price, subsequent buyers are unable to determine the cause of this change and can assume that it was (at least partially) caused by either unobservable changes of type k or by unobservable changes to amenities in the area. If their assumption is violated, it makes subsequent value estimations different than in a scenario with perfect information[9] either through learning form prices of other assets or through anchoring. Indeed, if prices in an area change after a renovation of type s affects the average price, two important effects will occur.

First, if the private quality of assets changes over time, prices of their peers will change even if the fundamentals of their peers remain constant. Therefore, if peer-price effects exist, they can contribute to house prices deviating from their fundamental values. In a simplified scenario with only two identical buildings, changing the private quality of one of them by renovating internally (a one-unit change in individual quality x) will change its own price by β while the price of the other property will change by $\frac{\beta\rho}{(1-\rho)}$.

Second, peer-price effects will lead to a multiplier effect. Equation 6 shows that the impact of an exogenous or correlated change in neighbourhood characteristics on house prices is magnified by $\frac{\rho}{1-\rho}$. This effect is similar to the 'social multiplier' (Glaeser et al. 2003) or the 'spatial multiplier' (Anselin 1988) in which the impact of exogenous factors on house prices is magnified by the peer-price effect. The multiplier effect is also a common feature in models of information asymmetry (Zhou and Lai 2009, Hasbrouck 1991). This effect has important implications for designing policy instruments that affect the housing market. However, it also means that researchers designing identification strategies to measure the impact of exogenous changes on house prices may need to consider the impact of endogenous peer-price effects.

In the appendix (section G), I discuss cases of equation 6 that violate the identifying assumptions (for example a case in which a change in characteristic of type s can be perfectly read from the price of the altered property).

[9] As noted above this is not necessarily a bias or error but simply a rational response to information frictions.

The final implication of equation 3 is that neither α nor ρ can be identified separately from a regression and both require an estimate of β to be derived. I therefore, turn to estimating an equation that yields estimates of both $\beta = \beta_1$ and $\rho = \frac{\beta_2}{\beta_1+\beta_2}$ by using exogenous changes of type s. This yields:

$$[\mathbf{7}]\ \Delta P_i = \beta_1 \Delta s_i + \beta_2 \frac{\sum_{j=1}^{N} \Delta s_j}{N} + \Delta \varepsilon_i$$

Note that β_2 captures the total impact of $\frac{\sum_{j=1}^{N} \Delta s_j}{N}$ on P_i. The implicit assumption (validated at a later stage) for estimating ρ is that this effect occurs completely through prices and has no impact on the amenity value in the area.

Empirical strategy

The most popular method of modelling house prices is using the hedonic model and the usual assumption of applying the model is that, given enough transactions of heterogeneous assets, the vector of shadow prices can be estimated by regressing transaction prices on characteristics of corresponding assets. The LIM model can be easily reconciled with the hedonic approach. In a LIM version of the hedonic model agents price the bundle of characteristics represented by an average house in a neighbourhood. To arrive at the hedonic value of a specific house they add or subtract the value of characteristics that distinguish it from the rest of the group. In this interpretation, the hedonic characteristics are not affected by prices of peer assets but their shadow prices are (Cochrane 2011)[10].

This study adopts several identification strategies that take advantage of information asymmetries arising from the structure of the English housing market. All approaches are based on a repeat sales model and the assumption that some houses change their individual characteristics between the

[10] Several papers demonstrate how the hedonic pricing theory can be extended to incorporate imperfect information. Examples include Kuminoff et al. (2008), Kask & Maani (1992) or Tse (2002). While an extended theoretical discussion is beyond the scope of the present paper, note that, with imperfect information, prices in the neighbourhood affect the willingness to pay as demonstrated by Pope (2008) and Kurminoff et al (2008).

first and the second transaction. Because the impact of changes in an asset's characteristics can impact prices of its peers through prices or characteristics of the neighbourhood, the focus is on separating the two channels from each other. The study uses renovations as an indication of changes in quality so the basic estimated equation takes the following form:

$$[\mathbf{7}]\ \Delta ln(P_{int}) = \beta_1 Ren_i + \beta_2 ln(\bar{R}_n) + \beta_3 TD_t + \beta_4 LD_n + \in_{it}$$

Where Ren is a dummy variable that signals renovation of property i. $\bar{R}_n$ is a proxy for the average return in the neighbourhood measured as the average ratio of the sale to purchase price in the neighbourhood n for all properties for which the second transaction occurred after property i is purchased and before it is sold (after the first transaction and before the second)[11]. TD (time dummy) is a standard approach to control for time-fixed effects in repeat sales models and takes the value of -1 in the period (quarter) of the first time and 1 in the period of the second transaction (see Case and Shiller 1989 for a summary and Cannaday et al. 2005 for a recent example), LD (location dummies) are based on postcodes (note that in the first-difference framework they reflect location-specific price trends) and ∈ is an error term. Note that all prices are in natural logarithms so that (if costs are ignored) the dependent variable can be interpreted as a logarithm of a return. In this setting, the main focus is on modelling the return as a function of the second transaction price under the assumption that it is affected by renovation (of self or/and of neighbours) while the purchase first transaction price is not.

In this framework, renovations are individual effects and the average return in a neighbourhood is the endogenous effect. Naturally, the main threat to identification is posed by exogenous effects correlated to renovations. In equation 7 they are reflected by time and location controls but all estimation strategies presented below employ various methods of controlling for these effects and testing their impact on the reported results. Following Manski (1993) and Ioannides (2011) it is

[11] An ideal way to measure the return in the area would be to take the difference between the average sales price in the neighbourhood at the time of the second and the first transaction. This however is not feasible when considering small areas in which transactions do not occur frequently.

possible to use equation 3 to identify the peer-price effects in a regression presented in equation 7 if the following conditions (assumptions) are satisfied:

1) $corr(\Delta x_i, \Delta X_N) = 0$, *(i∈N)* - characteristics of house *i* should not be correlated with characteristics of the neighbourhood – for example if a house renovates its façade it affects the characteristics of itself and of the neighbourhood simultaneously so the condition would be violated. This condition is notoriously problematic. To satisfy this requirement I take advantage of the fact that internal renovations are of type s (affect only the occupiers) and assume that $corr(\Delta s_i, \Delta X_N) = 0$.
2) $corr(\Delta x_i, \Delta x_j) = 0$, *(i,j∈N)* - characteristics of houses should not be correlated with each other – for example if renovations are encouraged by a subsidy program and all houses are renovated at the same time, their prices will be correlated due to participating in the program so the condition would be violated. To ensure that this condition is satisfied I use an IV for renovations to validate my main results.
3) $E(P_N|P_{iN}) = P_n, (i \in N)$ - the price of house i should not influence the average price in the neighbourhood used to estimate its own price – the peer-price effect in housing markets avoids this 'feedback loop' problem as houses are not traded very frequently so no transaction price in the sample affects itself through changing average prices in the area.
4) $E(\Delta P_i|\Delta x_i) = E(\Delta P_j|\Delta x_j)$, *(i, j∈N)* – the impact of renovating property i on its own price should be equal to the impact of renovating property j on its own price. The LIM model can only be solved (and the peer-price effect can only be expressed as $\rho = \frac{\beta_2}{\beta_1+\beta_2}$) if this condition is satisfied. This condition is satisfied by using a sample of homogenous terraced houses (see section 4).

Because conditions 1 and 2 are notoriously difficult to satisfy, the empirical strategy focuses mostly on addressing these two points.

Internal renovations

The first step in the identification strategy focuses on addressing condition 1. It is based on internal renovations and isolating the impact they have on nearby properties through prices of the renovated properties. By excluding renovations that can be seen from the outside, it is possible to isolate a change in the quality of an asset that plausibly does not affect the fundamental characteristics of other houses through any channel other than the return of the renovated property. Therefore, the first equation estimated in the study is:

$$[\mathbf{5}]\ \Delta ln(P_{int}) = \beta_1 iRen_i + \beta_2 ln(\bar{R}_n) + \beta_3 TD_t + \beta_4 LD_n + \epsilon_{it}$$

where $iRen_i$ denotes a renovation that cannot be seen from the outside. The primary focus is not on the impact of a renovation on the renovated house but on its neighbours. The tested hypothesis is that the renovation premium is transmitted through neighbourhood prices to prices of other properties.

I begin with a naïve specification and regress the return of property i on the average return in the neighbourhood. To control for all factors that can simultaneously affect them I instrument the change in the average price in the area with internal renovations. First, I use a reduced-form specification by substituting the average return $ln(\bar{R}_n)$ with a dummy variable that equals 1 if the nearest neighbour is internally renovated. I then estimate a 2SLS regression in which I instrument the return of the nearest neighbour with the fact of its renovation. Finally, I focus on the average return in the neighbourhood which I instrument with either the number or the percentage of properties which have been renovated internally in the neighbourhood.

In this framework, a significant effect of an internal renovation on the price of houses around it can be interpreted as evidence of the fact that transactions are endogenously influenced by prices of their adjacent buildings.

Timing of sales and the endogenous price effect

The next step addresses condition 1 by controlling for any unobserved exogenous effects that could be correlated with the endogenous effect and condition 2 by exploiting the timing of receiving information about the price as well as the renovation itself[12]. One potential issue with the above regression is that it could be driven by characteristics of the neighbourhood rather than prices. For example characteristics of the households who move into renovated properties may be different. In the appendix (section D) I show that location trends are effective in controlling for both contemporary and lagged area characteristics and (in section 5) I use data from the English Housing Survey to show that households who move into renovated properties are unlikely to be significantly different than others who move into the same neighbourhood. To further reinforce this point, I turn to a strategy designed to explicitly control for unobserved exogenous effects. It exploits the fact that there is a time lag between a transaction taking place and the price of this transaction being made publically available. In England and Wales, the Land Registry maintains and publishes records of all residential property transactions. By law, it has to be notified of all such transactions within 90 days and it releases the information to the public after internal processing. In practice, the fact that a delay is allowed in submitting transaction details to Land Registry leads to delays between transactions occurring and their details being publicly available. Since the peer-price signal between two properties cannot occur if the price of the peer building is unknown, prices of buildings sold at the same time should not be affected by each other's prices. However, all sales that occur after the transaction price is made public can be affected by it. Therefore, the next empirical equation estimated is:

$$[\mathbf{6}]\ \Delta ln(P_{int}) = \beta_1 iRen_i + \beta_5 NNRen_{it} + \beta_6 NNRen_{it-1} + \beta_7 NNRen_{it-f} + \beta_3 TD_t + \beta_4 LD_n + \in_{it}$$

where NNRen is a dummy variable that controls for the fact that the nearest neighbour of property i has been renovated and sold. I differentiate between three periods when the renovated neighbour is sold: t is the same period as property i, $(t-1)$ is 90 to 180 days before property i and $(t-f)$ is a period before $(t-1)$ but after property i is transacted for the first time. As before, the focus is on

[12] Note that even if renovations are correlated, the change exploited here is the interaction of a change and the timing of information about it being released which (if the timing is exogenous) mitigates some of the issues with renovations being correlated.

internal renovations that are unobservable to the public to satisfy condition 1. However, even if the condition is violated, the renovation impacts the amenity value of the neighbourhood immediately after it occurs while the impact through the peer-price effect takes place when the price is made public. Therefore, the different time periods of selling the nearest renovated neighbour indicate the endogenous signal contained in its price. No effect is expected when both transactions occur at the same time ($\beta_5 = 0$) but β_6 and β_7 are expected to be different from zero if there is a peer-price effect.

Note that coefficient β_5 can also be interpreted as a placebo test or as a test of any exogenous effects that occur at the time of the renovated property being sold. If a pair of properties sold at the same time is not found to have correlated prices, the effect does not occur through some correlated or exogenous effect that is not accurately reflected in the model. Factors such as characteristics of the buyers who move into renovated houses can be expected to be affecting the neighbourhood immediately after the transaction occurs and the new occupiers move in[13]. To ensure that the reported results are driven by endogenous price effects and not a lag of an unobserved exogenous effect, I choose two subsamples in which price information processing is delayed by administrative procedures. If the estimated peer-price effect takes longer to occur when information is processed more slowly, then it is likely caused by availability of price information.

Exogenous renovations

The final step in identifying peer-price effects is to test condition 2 and ensure that internal renovations are exogenous; not correlated with each other or any public characteristics of neighbourhoods. As explained above, if a decision to internally renovate a house and sell it in a specific time period is endogenous, then the peer-price effect cannot be identified. For example, if houses which are more likely to be renovated are also more likely to give a higher return, there might be a bias in the estimated coefficients. In order to ensure that the results are not biased in this

[13] Note that since the transaction date is a date at which the property legally changes ownership it is usually very close to the date of the new owner moving in.

way, renovations are instrumented with instances of accidental fires. Only fires that were followed by a refurbishment and (eventually) sold are considered. These cases are filtered to ensure that the fire did not affect any features of the house that can be seen from the outside and did not affect any surrounding properties. Since the size of the sample obtained in this way is small (83 observations), this model should be interpreted as a robustness check rather than a standalone estimation strategy. From the engineering perspective, a house that is renovated after the selected types of fires should not be structurally different from a renovated house. This suggests that renovations after a fire should have the same effect on prices as in the first approach but the decision to renovate is now highly unlikely to be correlated across houses.

This sample is also helpful in validating the assumption that internal renovations do not affect the value provided by other buildings directly. Because it is possible to track the exact date of a renovation induced by a fire, it is possible to show the impact of an exogenous renovation on prices in two periods 1) after the renovation takes place and 2) after the affected property is sold (and its price revealed). If the identifying assumption is true, there should be no effect on prices in the area after a property affected by a fire renovates until this property is sold.

4. Data

The key requirement for this study is to be able to track changes in quality of houses in the sample. This is achieved by using a dataset from the UK Department of Communities and Local Government (DCLG) on Energy Performance Certificates (EPC). Since 2007 it has been mandatory for every sold or rented house in England and Wales to have an EPC certificate (Regulations 2007). The process of obtaining the certificate requires a registered assessor to visit the property to inspect its features related to energy performance. Each assessment involves documenting a number of property characteristics that comprise an EPC rating. The records of each assessment are stored in the EPC Register. Until March 2017 the EPC register data was available to the public only as a centralized database and EPC ratings were only observable to potential and actual buyers or renters of specific properties at request.

Although DCLG states that an EPC certificate is not a very good measure of the quality of a house, the objective of this study is to track changes in quality rather than its levels at any point in time. Once received, an EPC rating is valid for 10 years. However, a new certification is required if there is a change in the number of parts designed or altered for separate use. A new certificate is also needed if any fixed services for heating, hot water, air-conditioning and mechanical ventilation are changed (Regulations 2007). In addition, higher ratings have been linked to higher selling and rental prices so if a renovation results in a higher EPC rating, the owner of the property has an incentive to obtain a new certificate (Fuerst et al. 2015). As a consequence, each building sold in the last 10 years has at least one EPC rating. Importantly, renovated buildings which were sold more than once are likely to have two certificates. Information from the EPC database is detailed enough to allow identifying changes in characteristics of a house that are visible from the outside. For the purpose of this study these were: replacing windows, renovating a roof and building an extension (there is no separate category for altering the façade). All other renovations identified using EPC data were classified as internal. An overview of 30 random properties using current and historic Google Street view photographs confirmed that the approach correctly distinguished between internal and external renovations (see appendix B for an example).

Asset-level house prices are from the Land Registry and include all properties sold more than once in a 10 year period starting on the 1st of August 2007 (when the EPC ratings were made mandatory). Because the objective of the study is to measure the impact of similar changes in assets of similar quality, the sample is limited to terraced houses (as required by condition 4 and as assumed in the proof of equation 4 in appendix A). At neighbourhood level, structural characteristics of terraced houses are likely to be of a similar nature across properties and significant differences in the impact renovations have on prices are unlikely. Moreover, significant external changes in a neighbourhood of homogenous properties are also rare (Lindenthal 2017). In fact, the UK planning system aims to 'maintain the amenity value of the neighbourhood' (DCLG 2012). This objective is often interpreted as a systematic preference for homogeneity and enforced as such by local planning bodies.

Although the main findings of the study can be replicated across England and Wales[14], the sample presented in this study focuses on 15 boroughs of London. This has several advantages (such as focusing on a relatively liquid market with multiple repeated transactions) but the main reason for restricting the sample is to ensure that assets in the sample are comparable with properties for which data on fire incidents is available. Information on which properties suffered from an accidental fire and were subsequently renovated and sold is not publicly available. For the purpose of this study, this information is obtained from cross-referencing three independent databases. The London Fire Brigade publishes fire incidents data on its website for all incidents it responds to since 2009. This includes detailed information about the type of the incident, its timing and the affected property. To protect the privacy of the occupants, locations of residential property fires are rounded so that Eastings and Northings give a 1 square kilometre area. I combine this data with the Land Registry database to find all properties sold in areas where fires occurred. The address of each of those houses is then entered into a search engine of local Building Regulations Approval Notifications[15]. Properties identified as ones that suffered from a fire, were subsequently renovated and eventually sold are ones that: 1) were sold in the $1km^2$ area affected by a fire 2) notified its local councils about construction works consistent with a fire incident recorded in the area within 6 months after the time of the incident given by the London Fire Brigade. Only five boroughs in London (Bromley, Wandsworth, City of Westminster, Hammersmith and Fulham, Kensington and Chelsea) allow the public to search their entire databases of Building Control Notifications thus these

[14] Although in the interest of space they are not presented in this study, the results have been replicated for the Local Authority District of Cambridgeshire.

[15] Building regulations approval is required to construct or alter most structures in England and Wales (Regulations 2010). This includes electrical work, replacing windows or changes to plumbing installations. In the case of a fire a notice of commencement of building work is usually required by the Local Authority at least two days before the work begins. The completed work is inspected and approved by the Local Authority.

are the main areas of interest for this study. To increase the size of the sample for which fires were not required but retain comparability between examined buildings, neighbouring boroughs are included so that the full sample contains all 15 boroughs of inner and south-east London.

Table 1 shows that the full sample contains almost 27,000 properties with repeated transactions with a mean increase in price of 6.1% and a large standard deviation caused by factors specific to individual assets or locations. Around 10% of the sample is renovated internally (2,679). External renovations are less popular (1,565) and combining external and internal renovations is relatively unpopular (769). This is not surprising as in terraced houses amenity value can be generated from facades of neighbouring buildings being identical and an external renovation of a single house may reduce this effect (Lindenthal 2017). 1,225 buildings are sold after their nearest neighbour renovates and sells. Out of 854 houses that suffered from a fire only 83 were subsequently sold and became the nearest neighbour to 39 transactions.

Table 1. Descriptive statistics.

Price change in	Observations	Mean	Std. Dev.	Min	Max
All properties	26,811	8.30%	22.54%	-78.10%	791.91%
Renovated properties	3,475	11.56%	23.93%	-78.10%	139.23%
Internally renovated properties	2,679	22.22%	13.67%	-78.10%	118.77%
Externally renovated properties	1,565	-3.5%	24.28%	-74.10%	139.23%
Properties where the nearest neighbor renovated	1,225	23.36%	13.38%	-29.47%	656.70%
Properties renovated after a fire	83	24.99%	9.76%	0.35%	57.01%

The sample is divided into 28 locations of around 1,000 properties based on clustering of contingent postcodes. Time dummies are based on quarters so there are 40 distinctive periods denoted in the sample. The “nearest neighbour transaction” (NN) is defined as the closest (by geographical distance) second sale transaction. A neighbourhood (NH) for each transaction is defined as all transactions within a 100m radius. Although these assumptions emphasize the focus of this study on close comparability between assets, the results are robust to changes in these definitions. To give an overview of how likely renovations are to be correlated in a neighbourhood and how this effect can be mitigated, Table 2 reports OLS regression results of a sold house being internally or externally renovated on renovations of the sold nearest neighbour. Note that this is not a direct correlation of renovations (as the exact timing of a renovation is unknown) but a correlation of houses that are both renovated and sold. It is clear from column 1 that internal renovations or sale decisions may be driven by a neighbourhood effect as properties are more likely to be internally renovated if their neighbours made changes to the interiors of their houses. However, column 2 shows that the timing of the nearest transaction does not change the correlation so that it does not matter if the nearest neighbour renovated and sold simultaneously or 9 months ago. This demonstrates that it is likely the fact of renovating that is correlated between neighbours and not the decision to sell a renovated house. This is not surprising as houses in the same area may share similar characteristics that determine the likelihood of renovating (such as age). Critically, column 3 shows that these effects can be effectively mitigated by using a location trend. While some correlation remains, the coefficients are lower by an order of magnitude and only one is statistically significant. A very different picture is presented for external renovations which, after controlling for location trends, do not seem to be correlated with internal renovations in the area. Finally, columns 7 to 9 show that the likelihood of the nearest neighbour being externally renovated is significantly lower when that property is also internally renovated. As expected, there is no impact of splitting this effect into time periods. This is consistent with the idea that in terraced houses internal and external renovations are driven by different factors.

Table 2. Correlation between renovations.

`	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)
Dep. Var. (renovation)	Own internal	Own internal	Own internal	Own external	Own external	Own external	NN external	NN external	NN external
NN Ren	0.197***			0.00174			-0.125***		
	(9.04)			(0.17)			(-5.80)		
NN Ren t		0.204***	0.204***		-0.0172	-0.0172		-0.107***	-0.107***
		(4.02)	(4.02)		(-0.93)	(-0.93)		(-5.91)	(-5.91)
NN Ren t-1		0.170***	0.170***		-0.0259	-0.0259		-0.110***	-0.110***
		(4.98)	(4.98)		(-1.55)	(-1.55)		(-5.31)	(-5.31)
NN Ren t-m		0.172**	0.172**		-0.00940	-0.00940		-0.110***	-0.110***
		(3.11)	(3.11)		(-0.43)	(-0.43)		(-5.69)	(-5.69)
Observations	26803	26803	26803	26803	26803	26803	26803	26803	26803
R-squared	0.075	0.041	0.041	0.012	0.012	0.012	0.041	0.027	0.027
Period FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Location TR			YES			YES			YES

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1, NN – nearest neighbour, Ren – internal renovation at any time, Ren t – internal renovation in the same period, Ren t-1 - internal renovation between 3 and 6 months before, Ren t-m - internal renovation more than 6 months before.

As stated earlier, I adopt two strategies of splitting the sample based on the delays I expect in releasing the price information. The first, exploits delays in central processing of documentation received by Land Registry. The institution regularly receives complaints related to significant delays in processing received documents. In official press statements Land Registry states that these delays are caused by staff shortages. Since the number of trained employees does not change significantly over time, the delays are especially severe when market activity is high. Therefore, the first sample in which the delay between transactions occurring and their prices having an impact on their neighbours is longer consists of transactions that occur during high market activity. High transaction volumes are deified as over 280,000 transactions per quarter. This categorizes 11 time periods (out of 40) as busy. In Figure 1, I show that this condition translates not only into selecting periods at the beginning and end of the sample (due to property cycles) but also in more active quarters (due to seasonal patterns). Since this is based on all transactions in England and Wales (not just the selected boroughs of London) it provides enough exogenous variation to assume that market activity levels are not endogenous to peer-price effects.

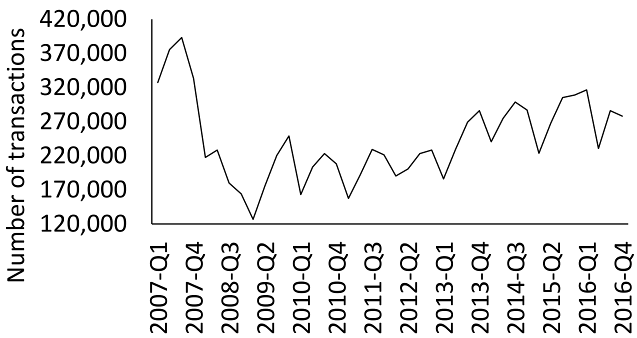

Figure 1. Number of transactions in England and Wales over time.

The second source of delays is based on the fact that Land Registry relies on documentation submitted to their processing centre by solicitors who handle transactions. Different local agents have different administrative procedures (some choose to submit at the end of each quarter, some may have a queue of documents that are processed and dispatched in order of their arrival, size, urgency or importance). These procedures determine how quickly transactions are submitted for processing to Land Registry and how quickly the price of the transaction is added to the public database. Since the procedures are firm-specific and many solicitors focus on serving their local areas there is a systematic difference between how quickly transactions from specific areas are revealed to the public (see appendix C for more detail). Although less robust than the market-activity approach, this method allows splitting the sample into slow and fast processing areas.

Critically, the data available for fire incidents allows classifying them into different categories based on the damage they inflict on the affected house. The fires used as instruments for internal renovations are small fires that affect no more than one room and do not damage the exterior of the house. They are usually caused by short circuits in electrical appliances and are random occurrences not correlated to building or area characteristics (Shea 2011). Appendix B gives a visual example of a buildings before and after a fire incident. Table 3 shows OLS results of regressing different characteristics of houses included in the sample on the fact that they have been affected by a fire. There is no evidence of small fire incidents being correlated to any one variable. When sector FE are included, energy efficiency levels have a significant coefficient but it needs to be noted that this variable is measured after the fire so it is likely affected by the renovation.

Table 3. Correlation between being affected by a fire and house characteristics.

	(I) Ln(size)	(II) Rooms	(III) Ln(EE)	(IV) Heated rooms	(V) Fireplace	(VI) Ln(size)	(VII) Rooms	(VIII) Ln(EE)	(IX) Heated rooms	(X) Fireplace
Fire dummy	-0.051	0.068	0.041	0.148	-0.018	-0.0007	0.202	0.087*	0.179	-0.052
	(-1.11)	(0.37)	(1.13)	(0.67)	(-0.33)	(-0.01)	(0.97)	(2.00)	(0.71)	(-0.82)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sect FE						Yes	Yes	Yes	Yes	Yes
N	72675	72018	75105	72018	75105	72674	72017	75104	72017	75104
R^2	0.005	0.001	0.006	0.005	0.007	0.224	0.132	0.026	0.095	0.065

t statistics in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. The table reports regression results of variables listed in the second row on the fire dummy taking the value of 1 if the property has been affected by a fire and zero otherwise and year of certification fixed effects. Columns VI to X also include a postcode sector fixed effect (Sect FE). The sample includes all recorded certificates of terraced houses in postcode districts affected by fires. Differences in the number of observations come from availability of data for specific characteristics of a house. Size is measured in square meters, Rooms refers to the number of rooms in the property, EE stands for the energy efficiency rating given by the EPC, Heated rooms give the number of heated rooms and Fireplace is a dummy variable taking the value of one if the property has a fireplace. Note that the sample size is larger as these are not only the repeated sale transactions but all buildings in the EPC database.

5. Results

Table 4 presents OLS and 2SLS results of the main specification. The first important result is that internally renovating a house adds around 5% to the price of the renovated property[16]. This finding remains consistent throughout all specifications.

Table 4 also shows that returns of neighbouring properties are correlated even when changes in their returns are induced by internal renovations. The first step is to show an OLS (column I) with location trends and time controls which demonstrates that returns of neighbouring properties are strongly correlated. Column II uses a reduced-form OLS specification in which the return of the nearest neighbour is replaced by a dummy variable that takes the value of one if the nearest neighbour is internally renovated. Next, I use internal renovations of the nearest neighbour as an instrument for their return. Column III shows not only that the first-stage results are consistent with the earlier expectation of the impact of the nearest neighbour renovation on their own price, but

[16] Note that the focus is on the return on property i which (as defined in section 3) is determined by its sale (second transaction) price. Coefficients of explanatory variables can therefore be interpreted as increasing the price and the return equally.

also that this price signal affects subsequent transactions. Columns IV and VI separate the two types of renovations (internal and external) and show that only effects of internal ones are transmitted through price shocks. Specifically, the premium for internally renovating a property increases the price of its nearest neighbour. Column V provides a result consistent with the expectation that when the renovation of the nearest neighbour is visible from the outside, it does not affect other buildings through prices. If at all, it is likely that this occurs through exogenous neighbourhood effects. However, the impact of an external renovation is not identified in this model as it interacts with location characteristics[17]. In summary, the magnitude of the effect reported in columns III-VI suggests that an internal renovation increases the price of the renovated house by around 5% while the neighbour receives a premium of around 2%.

Focusing on neighbourhoods (rather than nearest neighbours) gives similar results. In an OLS, the average return of properties sold within 100m has a significant and positive effect (column VII). Instrumenting it with the number (or the percentage) of internally renovated properties in the area shows that renovations induce a peer-price effect. Note that although in principle growing prices and renovations in a neighbourhood can be endogenous (violate conditions 1 and 2 from section 3). The presented regressions have several ways of addressing this issue: 1) Property fixed-effects and location trends should capture not only time-fixed differences between areas but also any trends including a tendency to renovate. 2) It is unlikely that prices of peers would be correlated to only internal renovations and the reported results control for external renovations. 3) The presented models control for the renovation of the property whose price is estimated as well as of its neighbours. Therefore, even if renovations are correlated, the impact of this is mitigated. The fact that prices increase with additional instances of internal renovations, shows the additionality of each

[17] If a property renovates externally it sells at a discount compared to other properties in the same location. Although this could be because it receives a discount for standing out (Lindenthal 2017) or because it has a lower internal standard than its neighbours (or than expected from an externally renovated house) the effect cannot be inferred from these results as the whole neighbourhood is affected by the renovation.

peer-price signal. As predicted by the theory, the effect is also weaker in locations where fewer transactions occur (see appendix F for more details).

Table 4 –Regression results of the change in house prices as a function of internal renovations of neighbours – instrumenting renovation effects (instrumented variables are in bold).

	I	II	III	IV	V	VI	VII	VIII	IX
	OLS	*OLS*	*2SLS*	*2SLS*	*2SLS*	*2SLS*	*OLS*	*2SLS*	*2SLS*
Variable:						**Second stage**			
Internal renovation	*0.0669****	*0.0526****	*0.0630****	*0.0632****	*0.0740****	*0.0518****	*0.0639****	*0.0597****	*0.0570****
	(16.83)	*(10.24)*	*(14.91)*	*(15.00)*	*(13.98)*	*(8.53)*	*(16.29)*	*(14.71)*	*(13.54)*
NN internal renovation		*0.0284****							
		(6.56)							
NN external renovation		*0.0319****							
		(4.62)							
Ln Return of NN	*0.157****		***0.517******	***0.499******	***-0.510***	***1.570******			
	(18.23)		***(5.14)***	***(4.97)***	***(-1.83)***	***(7.26)***			
Ln Average return in NH							*0.271****	***0.511******	***0.670******
							(30.21)	***(10.28)***	***(10.42)***
Instrument:						**First stage**			
NN internal renovation			*0.041****	*0.028****					
			(13.29)	*(14.40)*					
NN external renovation			*0.003*		*-0.025****				
			(0.61)		*(-5.57)*				
Number of internal renovations in NH									*0.0175****
									(23.88)
Percentage of NH internally renovated						*0.043****		*0.132****	
						(9.19)		*(30.39)*	
Time controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
External self-renovation dummy	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Location controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	26811	26811	26811	26811	26811	26811	26811	26811	26811
R^2	0.288	0.281					0.303		

Notes: t-statistics in parentheses, NN stands for the Nearest Neighbour, NH stands for Neighbourhood (100m radius from property i), all dummy variables are underlined, all instrumented variables are in bold, significance is denoted at * p<0.05, ** p<0.01, *** p<0.001. Column I presents OLS results of a reduced form model with the return of the nearest neighbour. Column II shows results of a 2SLS regression in which the return of the nearest neighbour is replaced by internal and external renovations of the neighbour. In column III the return of NN is instrumented with its internal and external renovations. Columns IV and V use the same instruments in two separate regressions. Column VI uses the percentage of renovations in the neighbourhood as an instrument for the return of the nearest neighbour. Column VII gives results of a naïve regression that uses the average return in the neighbourhood as an independent variable. Columns VIII and IX instrument this variable with the number and the percentage of internal renovations in the neighbourhood.

Timing

To further reinforce the claim that the reported peer-price result is not driven by an unobserved exogenous effect, I explore the timing differential between transaction dates and price publication times in table 5. Column I provides a benchmark (similar to table 4), column II shows that when the nearest neighbour is renovated and sells at the same time, the renovation has no impact on prices of adjacent buildings. Further results (columns III to VI) show that prices of properties sold at the same time are not correlated (after controlling for time and location fixed effects) even when one of the properties is internally renovated. This suggests that no peer effect occurs without the signal contained in the price being revealed. However, selling a property three months after a transaction of a nearby renovated house, increases the return significantly. Following the theory outlined in section 3, the fact that the correlation materialises when transaction prices are made public is consistent with the peer-price effect. To show that the impact is not limited to any one time period after the price is revealed column III splits the effect into different time periods. The impact increases after additional 3 months but does not change thereafter. Other than the peer-price effect, the only explanation that would be consistent with this result is if the return of the renovated property is affected by a feature of its area (X_N) and the return of the house that sells 3 months later is affected by the same characteristic but with a delay (the lag value of X_N). In appendix D, I show that area trends are effective in capturing both contemporaneous and lagged unobserved area characteristics which makes this explanation very unlikely. However, to further reinforce the claim that the results are driven by price disclosure and not area characteristics, column VI shows results only for periods where market activity was high and Land Registry was expected to delay price publications. The results show that in those periods internal renovations did not affect prices of surrounding houses for two quarters but had the expected significant effect afterwards. Moreover, in columns IV and V the sample is split into two subsamples based on how quickly the data was released after the transactions occurred in 2018. As expected, locations classified as fast are affected by the peer-price effect within 3 months while it takes 6 months to take hold in 'slow' areas.

Table 5 –Regression results of the change in house prices as a function of internal renovations of neighbours – exploiting the lag between transaction date and price announcement.

	I	*II*	*III*	*IV*	*V*	*VI*
Sample	*Full*	*Full*	*Full*	*Slow*	*Not slow*	*Busy*
Internal renovation	*0.0824****	*0.0836****	*0.0835****	*0.0526****	*0.111****	*0.0840****
	(0.00435)	*(0.00430)*	*(0.00430)*	*(0.00593)*	*(0.00604)*	*(0.00597)*
NN internal renovation	*0.0129***					
	(0.00410)					
NN renovated and sold 3 or more months ago		*0.0556****				
		(0.0113)				
NN renovated and sold in the same period		*0.0170*	*0.0170*	*0.0133*	*0.0134*	*0.0168*
		(0.0140)	*(0.0140)*	*(0.0194)*	*(0.0194)*	*(0.0188)*
NN renovated and sold 3 months ago			*0.0450***	*0.0218*	*0.0555***	*0.0324*
			(0.0150)	*(0.0237)*	*(0.0191)*	*(0.0200)*
NN renovated and sold 6 or more months ago			*0.0690****	*0.0814****	*0.0506**	*0.0753****
			(0.0168)	*(0.0230)*	*(0.0236)*	*(0.0226)*
Time controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Ext renovation	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Location controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
N	*26811*	*26811*	*26811*	*9009*	*17802*	*13729*
R-sq	*0.277*	*0.278*	*0.278*	*0.317*	*0.250*	*0.289*

Notes: Standard errors in parentheses, NN stands for the Nearest Neighbour, all dummy variables are underlined, significance is denoted at * p<0.05, ** p<0.01, *** p<0.001. Column I presents results that show the average impact of an internal renovation on the renovated property. Ext renovation is a dummy denoting an external renovation of self. In column II the return of the nearest neighbour is approximated by the fact that it is internally renovated. Column III shows the average effect of the impact of an internally renovated property on its neighbour that occurs with a lag of three months or more. In column IV the renovation dummy is decomposed into nearest neighbours who are sold at different times in relation to property i. Columns V and VI show the sample broken down into two sub samples; one where price information is released with a longer delay and the rest of the sample. Column VII presents results only for the 10 time periods when the market activity was the highest (and transaction price processing lags the longest).

Further robustness tests: accidental small fires and internal renovations

The claim that the above results are not affected by internal renovations being endogenous is tested in table 6 which uses Building Control Notices rather than EPC data to denote internal renovations and focuses on renovations induced by instances of accidental fires. Variables corresponding to fire renovations are significant and positive for both the affected properties and their neighbours. Their magnitude is also consistent with earlier estimations (although the effect of renovating on own price is smaller). In practice, only one fire occurs per postcode so this table compares transactions made before the incident to deals made after renovations are completed and the building sold in multiple postcodes. Although the size of the sample is limited and the results need to be interpreted with this constraint in mind, the estimated coefficients are consistent with earlier models. When an internal renovation is induced by a fire, the selling price of the property increases and this effect is carried forward to its neighbours through changes in average prices in the neighbourhood. It is clear that when instrumented with instances of accidental fires, internal renovations still have a positive effect on prices of buildings in the neighbourhood.

Table 6 –Regression results of the change in house prices as a function of internal renovations of neighbours – Accidental fires as an instrument for renovations.

Second stage		
Variable	Estimation results	
	I	*II*
Average price in NH	***0.691***$^{\$}$	***0.951******
	(1.73)	***(4.76)***
First stage		
Instrument	Estimation results	
NN renovated after fire	*0.0732****	
	(3.35)	
Percentage of renovations after fire in NH		*0.0998****
		(31.96)
Time controls	Yes	Yes
Location controls	Yes	Yes
N	26803	26803

Notes: Standard errors in parentheses, NN stands for the Nearest Neighbour, NH stands for Neighbourhood (100m radius from property i), all dummy variables are underlined, all instrumented variables are in bold, significance is denoted at $ p<0.1, * p<0.05, ** p<0.01, *** p<0.001. In column I a 2SLS instruments the average return in the neighbourhood with the fact of a renovation after a fire and the percentage of houses affected in this way. Column II is a 2SLS regression that instruments the average return in the neighbourhood with the percentage and the number of renovations in the neighbourhood.

Once more, the main concern for identification is the possibility of an exogenous effect of the fire affecting neighbouring buildings through channels other than price. However, as with external renovations an exogenous effect of a fire should materialize at the time of the incident (or shortly after) and not when the renovated property is sold as it does in table 6. To give further support to this process, I exploit the rich dataset of fire incidents made available by the London Fire Brigade and examine the impact of fires on prices of nearby houses. Specifically, I test the difference between the impacts of events that affect the exterior of a house against fires that affect only the interior.

Table 7 classifies accidental fires as large (ones that affect the exterior of a house or spread and affect more than one room) or small (as used in table 6). The date of each event is available and the table reports their impact starting immediately afterwards. Column I presents the impact of each event on house prices and shows that after large fires prices in the surrounding area are lower[18], while after small fires prices do not change. This validates the identification strategy that assumes that small fires are random accidents unrelated to any area characteristics either before or after they occur. Column II shows that internal renovations only affect prices of surrounding buildings after the affected property is sold. This is equivalent to the results in table 6 but the renovation after a small fire dummy variable is now substituted for the return in the neighbourhood (rather than using a 2SLS). The difference between effects of small and big fires is even more explicit in column 3. This is consistent with the assumption that using small accidental fires as an instrument satisfies conditions 1 and 2. Since small fires are known to the neighbourhood because they require a report from the Fire Brigade, the results from table 7 also validate the assumption that internal renovations do not affect the fundamental value of other properties directly. If they did, prices would increase after properties are renovated and not after they are sold.

[18] Note that this is an exogenous effect so its impact on prices is not identified from regressions presented in this study.

Table 7 –Regression results of the impact of a fire in a neighbourhood on house prices.

VARIABLES	*I*	*II*	*III*
Small fire in NH	*-0.0124*		*-0.0123*
	(0.0102)		*(0.0102)*
Large fire in NH	*-0.0237****		*-0.0237****
	(0.00400)		*(0.00400)*
NN renovated and sold after fire		*0.0785**	*0.0779**
		(0.0313)	*(0.0313)*
Observations	*26803*	*26803*	*26803*
R-squared	*0.112*	*0.111*	*0.113*
Period FE	*YES*	*YES*	*YES*
Location trends	*YES*	*YES*	*YES*

Notes: Standard errors in parentheses, Dummy variables are underlined, NN stands for the Nearest Neighbour, NH stands for Neighbourhood (100m radius from property i), all dummy variables are underlined, significance is denoted at * p<0.05, ** p<0.01, *** p<0.001. Columns I presents results of the impact of an accidental fire in the neighbourhood on the price of the valued property. Column II reiterates the impact of renovations after a fire on the price of the neighbours. Column 3 presents the impact of renovations after a fire alongside the impact of a fire in the neighbourhood. Small and Big fires are dummy variables that equal one if a fire of the corresponding magnitude affected the property at any time between its first and second transaction.

Quantifying the peer-price and multiplier effects

Overall, the results suggest that the impact of renovating a property (the individual effect) on its own price is a premium of around 5% and the impact on the price of its nearest neighbour is around 2%. Importantly, the latter is a coefficient of a regression and not the magnitude of the endogenous effect. Substituting the above estimates into equation 6 and solving for ρ results in an estimate of 0.25. The advantage of using a homogenous sample of terraced houses is that the effect is consistent across locations and transactions[19]. This supports the assumption that the change in the quality of any two renovated properties is the same so that an internal renovation affects any renovated property in the sample in same way and gives a consistent estimate of β. This suggest that houses receive a 0.25% premium from every 1% increase in the price of their peers. Naturally, this is an estimate for the sample and its transferability to other settings and price shocks depends on the mechanics of the peer-price effect.

It is also important to note that the identification strategy allows isolating the impact of one price on another but does not distinguish between perfect learning from prices of other assets and endogenous interactions (learning with a bias or anchoring). To interpret the results as *endogenous*

[19] This is evidenced in the fact that the impact of internal renovations on the renovated house in the first stage results is very close to its impact in the second stage.

interactions it is necessary to satisfy the assumption that internal renovations do not affect the value of housing services offered by surrounding buildings. This statement finds support in the data:

1) There is strong effect at the time when the price is revealed. This can only be attributed to the direct impact of an internal renovation if there buyer learns something about the value of the house they are purchasing that they cannot learn without the price signal (for example from the seller or the agent). Since the seller is likely to know about internal renovations in the area and has an incentive to inform the buyer (to elicit a higher price), the buyer does not need to read this information from the price.
2) Table 7 demonstrates that an internal renovation induced by a fire has no impact on prices in the area until the renovated property is sold. This shows that an internal renovation has no direct impact on other properties. This contrasts with big fires that affect the area immediately.
3) To investigate the possibility that the price of an internally renovated property informs other buyers about private characteristics of the household that moves into the renovated property, the appendix (section E) compares the income of people who move into renovated and non-renovated houses. Using income as the most important individual characteristic that is not directly observable to neighbours, shows that it is orthogonal to renovations.

The endogenous price interaction has several important implications. For example, as indicated by the reduced form in equation 6, the endogenous price interactions lead to a multiplier effect that amplifies the impact of changes in area characteristics on house prices. Equation 6 shows explicitly that, due to the multiplier effect, a peer-price effect of $\rho = 0.25$ increases the impact of exogenous changes on house prices by one third. Consequently, the total effect of changing neighbourhood characteristics on prices in the area is a combination of the capitalized value of the change in fundamentals and the impact of the multiplier effect. Naturally, when the change in the neighbourhood characteristic is easily observable (such as a school or a park) the multiplier might be weaker (or not exist at all) as it is easier to adjust for the impact of that amenity on prices.

This paper motivates the deviation from fundamental price by demonstrating that when gathering and processing information about house characteristics is costly, buyers and sellers may choose to use average prices of similar assets as a benchmark. In this context, the bias (positive or negative) of using prices of peers as a guide is less costly to them than estimating the fundamental value of the purchased property.

In addition, if the endogenous price interactions are driven by the fundamental characteristics of house prices being priced differently under different prices of neighbours, local trends can materialize in prices of properties whose fundamental characteristics remain constant. This is in line with the literature on endogenous price trends in other markets (Lei et al. 2001, Case and Shiller 1989). Those trends may be induced even if prices of nearby transactions are affected by unique characteristics of the properties or transactions such as financing arrangements, buyer and seller with unique preferences or property-specific events (such as internal renovations). As shown in the appendix (section F), it can be small if numerous unaffected transactions occur in the area but increase when little information is available from 'unbiased' trades. Since the number of possible unique and unobservable factors that increase or decrease property prices is large, this process also explains why, on average, house prices can be more volatile than their fundamental characteristics.

A notable limitation of this study is that it provides no guidance on how peer assets should be selected.

6. Conclusions

This study finds that house prices of properties located close to each other are correlated through an endogenous price effect. The empirical strategy rests on a model that represents the price of an asset as a function of not only its own features but also of characteristics of its peers. By studying internal renovations, it focuses on changes to asset quality that are not observable to buyers of other houses. Although buyers cannot observe internal renovations in the area, they can observe prices of the renovated houses. I find a strong effect of an internal renovation on prices of surrounding dwellings and show that this effect is transmitted through price. The finding remains robust to different identification approaches and model specifications.

The fact that the peer-price effect is endogenous suggests that it has several important economic implications. The first is that it offers empirical support to several macroeconomic theories of the impact of peer effects on house prices. Specifically, it shows that, as theorised by Shiller (2014), house prices may follow trends even without any new information. In addition, the total impact of any new information on house prices will be amplified due to the multiplier effect. Together, the two effects could increase the volatility of house prices above the level predicted by changes in economic fundamentals (Glaeser & Nathanson 2015).

The most significant policy implication is that policy interventions related to house prices need to take this additional determinant of house prices into account. For example, the peer-price effect can transmit prices spatially and result in even the most localised policies having spatial spill overs. In addition, the multiplier effect will magnify the impact of any actions that affect house prices. Finally, it is also possible that new policy instruments can be created for the housing market. For example, withholding information on transaction prices could reduce excess price volatility in periods when strong trends become a concern. Although controversial, this would be very similar to the emergency procedure of suspending trading of an asset in the stock market (or trading halts before news announcements).

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Appendix

A. **Proof of equation 3.**

Although most studies of peer effects use the linear-in-means model presented by Manski (1993), I take advantage of the fact that in housing markets a transaction is unlikely to affect itself through the endogenous effect (due to low frequency of transactions) to simplify the identification approach. In the first-difference version of equation 1, the price of property i is determined by its own unique characteristics, characteristics of the neighbourhood X and the average return in the area:

$$[\mathbf{1.1}]\ \Delta P_{it} = \beta\Delta x_{it} + \rho\Delta P_{nt} + \alpha\Delta X_{nt} + \Delta\varepsilon_{it}$$

Note that the average return in the area is determined prior to the transaction by other transactions:

$$[\mathbf{2.1}]\ \Delta P_{nt} = \frac{\sum_{j=1}^{\Delta N}\Delta P_{jt}}{\Delta N}$$

Where ΔN is the number of transactions in the neighbourhood that occurred in neighbourhood n between the first and the second transactions of house i. Equation 1.1 can be substituted for ΔP_{jt}:

$$[\mathbf{1.2}]\ \Delta P_{nt} = \frac{\sum_{j=1}^{\Delta N}(\beta\Delta x_{jt} + \rho\Delta P_{nt} + \alpha\Delta X_{nt} + \Delta\varepsilon_{it})}{\Delta N}$$

Because I limit my study to a sample of homogenous terraced houses, the change in characteristics of the neighbourhood will have an identical effect on all transactions within it so $\frac{\sum_{j=1}^{\Delta N}\alpha\Delta X_{nt}}{\Delta N} = \alpha\Delta X_{nt}$. Note also that to facilitate a simple solution, I introduce an additional simplifying assumption that all houses in the neighbourhood are transacted for the second time at the same time t (but before property i). The average price of the neighbourhood of any property can be treated as exogenous to that property for all transactions that occur around the same time so $\frac{\sum_{j=1}^{\Delta N}\rho\Delta P_{nt}}{\Delta N} = \rho\Delta P_{nt}$. By assuming that all changes to neighbours happen at the same time (time t) I ignore the fact that the changes (e.g. renovations) may have occurred in a particular order and that this order could have an effect on average prices. While the latter explanation would be closer to a general process, in the present study I focus on the variation coming from a change in x_j that has the same impact on ΔP_j irrespective of the time of the second transaction. In the empirical specification, I address this problem by presenting results in which the neighbourhood is defined as only the nearest neighbour[20]. With only the change in price of the nearest neighbour used as a neighbourhood price benchmark, there is no interaction between prices of neighbours and $\Delta P_j = \Delta P_n$ for all periods of the second transaction of the neighbour as long as they are between the first and the second transaction of property i. Therefore simplifying equation 1.2 and solving for P_n gives:

$$[\mathbf{1.3}]\ \Delta P_{nt} = \frac{\beta}{1-\rho}\frac{\sum_{j=1}^{\Delta N}\Delta x_{jt}}{\Delta N} + \frac{\alpha}{1-\rho}\Delta X_{nt} + \frac{\sum_{j=1}^{\Delta N}\Delta \varepsilon_{it}}{\Delta N}$$

Substituting equation 1.3 into equation 1 gives equation 3:

$$[\mathbf{1.4}]\ \Delta P_{it} = \beta\Delta x_{it} + \alpha(1+\frac{\rho}{1-\rho})\Delta X_{nt} + \frac{\beta\rho}{(1-\rho)}\frac{\sum_{j=1}^{\Delta N}\Delta x_{jt}}{\Delta N} + \frac{\sum_{j=1}^{\Delta N}\Delta \varepsilon_{it}}{\Delta N} + \Delta\varepsilon_{it}$$

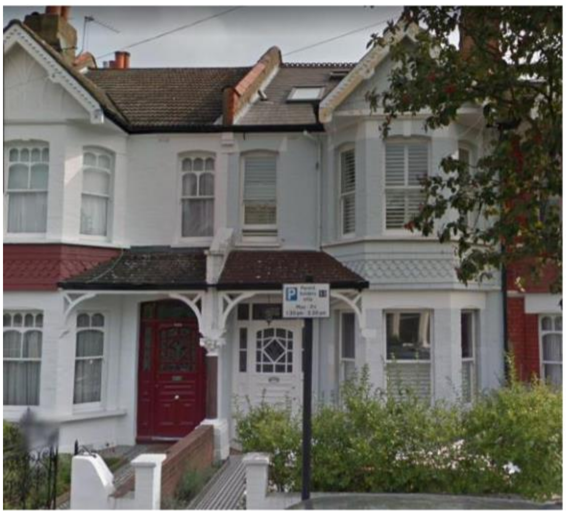
Simplifying the error term to $\frac{\sum_{j=1}^{\Delta N}\Delta \varepsilon_{it}}{\Delta N} + \Delta\varepsilon_{it} = \Delta\epsilon_{it}$ gives an equation that can be taken to the data:

$$[\mathbf{1.5}]\ \Delta P_{it} = \beta\Delta x_{it} + \alpha(1+\frac{\rho}{1-\rho})\Delta X_{nt} + \frac{\beta\rho}{(1-\rho)}\frac{\sum_{j=1}^{\Delta N}\Delta x_{jt}}{\Delta N} + \Delta\epsilon_{it}$$

[20] Using the second definition of a neighbourhood (all transactions within 100m) could be biased if the temporal distribution of renovations in the chain of transactions is correlated with the number of renovations. This is why I present 'balancing' statistics to demonstrate that there appears to be no evidence of renovations happening in sequence amongst close neighbours.

B. **Summary of visual validation of the EPC and fire renovation data.**

Below are two sets of photographs of houses marked in the data of the present study as going through a renovation between the first and the second transaction using EPC data. They are taken from Google Street View. The one on the left is taken from a year before the first transaction and the one on the right after the second so that the pictures show the impact of a renovation. The first row shows a renovation marked as both internal and external. The pictures clearly show that the change is visible from the outside and affects the amenity value of the neighbourhood. The second row shows a house marked as renovated internally. Note that in the second picture there is an advertising sign displayed by the contractors who completed the works (I chose this photograph to avoid the possibility that no renovation occurred) but no other visible signals of an improvement are visible from the outside.


The below pictures show houses that have been renovated after an accidental fire. Note that although minor details change over time (a gate to the garden is replaced in the first row and a fire alarm is installed in the second row) there is no material difference in how the houses look from the outside.


The house affected by a fire is the one in the middle.


C. **Spatial and temporal differences in delays in releasing price information**

As the speed at which information about transaction prices is processed and submitted to Land Registry may depend on the procedures of local institutions that operate in selected areas, prices in some locations may take longer to become public than in others. To identify where price disclosure may have been more likely to take longer I use current delays in this process. More specifically, I compare four recent downloads of the public database from different time periods (Sep 2017, Dec 2017, March 2018 and June 2018) to show that (in all areas used in this study) on average 17% of transactions that occurred in Sep 2017 (100% is the number of transactions available publically in June 2018) were available within three months of the transaction date and over 80% after six months. However, in several postcode areas these fractions were as low as 9% and 42% suggesting that in these locations transaction prices were released with a longer delay. This delay is not expected to be correlated with renovations or any other factor that may directly affect the peer-price effect. If prices in some areas take systematically longer to release the peer-price effect in those places should take be delayed.

D. **Controlling for current and lagged neighbourhood characteristics using time and location effects**

Section 5 shows that an internal renovation affects the nearest neighbour three months after the renovated property is sold but not earlier. One concern with attributing this effect to the peer-price effect is that the impact of renovations on prices of its neighbours could occur through lagged neighbourhood characteristics. While the delay in public disclosure is a sound basis for the price of the renovated property to affect its neighbours with a 3 month lag, it is also possible that renovations impact area characteristics and that these new characteristics affect prices with a lag.

In this study area characteristics are treated mostly as unobservable and are not identified in regressions presented in this paper. However, to demonstrate that location trends are effective in controlling for the unobserved characteristics table D1 shows that they are better at reflecting unobserved area characteristics than the return of neighbouring properties sold both in the same time period and 3 months earlier.

Column 1 shows that without area trends the return of the nearest neighbour is statistically significant and positive. The contemporary and lagged transactions have the same impact of around

0.055. This is consistent with the expectation that this correlation may me reflecting a common unobserved area characteristic rather than an interaction between prices. Indeed, when area trends are introduced the impact of both is zero. This shows that on average the correlation between neighbouring buildings is driven by area characteristics and this can be reflected using area trends.

Column 3 shows that when renovation dummy variables are used without controlling for area trends, all effects are significant and positive. In column 4, we can see that with area trends all coefficients are reduced to zero which is expected if their impact is reflected in area characteristics.

Table D1 –Regression results of the change in house prices as a function of internal renovations of neighbours – testing the robustness of table 2 estimates to the presence of lags of unobserved neighbourhood effects.

VARIABLES	*I*	*II*	*III*	*IV*
Return of the NN sold <u>*no earlier*</u> than 3 months before	*0.141*** *(2.86)*	*0.0312* *(0.65)*		
Return of the NN sold <u>*earlier*</u> than 3 months before	*0.148**** *(3.38)*	*0.0779* *(1.82)*		
NN renovated internally and sold <u>*no earlier*</u> than 3 months before			*0.0272** *(2.45)*	*-0.0000958* *(-0.01)*
NN renovated internally and sold <u>*earlier*</u> than 3 months before			*0.0362*** *(3.02)*	*0.0147* *(1.25)*
Observations	*26811*	*26811*	*26811*	*26811*
R-squared	*0.529*	*0.560*	*0.529*	*0.560*
Period FE	*YES*	*YES*	*YES*	*YES*
Location trends		*YES*		*YES*

Notes: Standard errors in parentheses, NN stands for the Nearest Neighbour, all dummy variables are underlined, significance is denoted at * p<0.05, ** p<0.01, *** p<0.001. Column I presents results that show the average impact of an internal renovation on the renovated property. In column II the return of the nearest neighbour is approximated by the fact that it is internally renovated. Column III shows the average effect of the impact of an internally renovated property on its neighbour that occurs with a lag of three months or more. In column IV the renovation dummy is decomposed into nearest neighbours who are sold at different times in relation to property i.

E. **Renovated houses and characteristics of their buyers**

One possible channel through which a sale of a property could affect the price of its neighbours is through the impact of the people who move in on the neighbourhood. When a property is sold its residents usually change at the same time so it is difficult to separate the impact of these events on prices in the neighbourhood. One possible concern for the identification strategy is that internally renovated properties could attract residents who positively affect their neighbourhoods. For example, since renovated properties are more expensive they may attract buyers with higher incomes. If residents with higher income positively affect the value of the neighbourhood, renovations could affect prices of other buildings through an exogenous effect (change in the neighbourhood characteristics) and not through an endogenous interaction of prices.

To show that renovated properties do not attract buyers with higher incomes I use data from the English Housing Survey. The data shows that in a sample of over 7,200 respondents who bought a house in 2016 income was not correlated with the potential of their property for comprehensive repairs. The dataset reports the cost of potential urgent and comprehensive repairs reported by professional surveyors for each of the buildings in the sample. Urgent repairs are work which needs to be undertaken to tackle problems presenting a risk to health, safety, security or further deterioration in the short term (for example leaking roofs, broken locks to external doors, or cracked socket covers). Comprehensive repair refers to any replacements the surveyor has assessed as being needed in the next 10 years. Internal renovations used in the main body of this study are unlikely to qualify as urgent.

Table E1 shows that while buyers with higher incomes are less likely to move into properties that require urgent repairs, income is not correlated with a need for comprehensive repairs. Specially, I regress the cost of urgent and compressive repairs on four dummy variables that correspond to income of the resident being in the two lowest and highest quintiles of the sample's income distribution. Omitting the middle quintile makes it the baseline in this regression, so that the coefficient of each quintile shows the difference to the middle quintile.

The result is not unexpected as an internal renovation is not an obvious preference for higher income households. Buyers of properties that are not freshly renovated may simply have a preference to renovate at a later date or according to their own preference.

Note also that my identification strategy rests on internal renovations and that I find no impact of an external refurbishments. This means that to attribute the reported peer-price effect to unobserved characteristics of buyers of internally renovated properties, these characteristics would have to be exclusive to internal renovations.

Nevertheless, the available data does not allow me to rule out the possibility that households who move into internally renovated houses have a positive impact on characteristics of their neighbourhoods as long as these; 1) are correlated with internal but not external renovations 2) on average do not materialize earlier than 3 months after the property changes hands 3) take longer to materialize when the housing market is more active and in places where prices appear on the Land Registry's reports with a longer delay.

Table E1. Correlation between refurbishment costs and income of buyers.

	(I) Urgent	(II) Comprehensive
Income Quintile 1	-0.130	-1.217
	(0.827)	*(2.270)*
Income Quintile 2	-0.187	1.972
	(0.852)	*(2.339)*
Income Quintile 4	-1.969**	-3.598
	(0.945)	*(2.594)*
Income Quintile 5	-4.404***	-4.609
	(1.109)	*(3.043)*
Constant	10.52***	45.05***
	(0.622)	*(1.708)*
Observations	7,190	7,190
R-squared	0.003	0.001

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1, in both models the dependent variable is the estimated cost of potential repairs, quintiles refer to the level of income of the buyer which is divided into five equal quintiles, with 1 being the lowest and 5 the highest, The middle quintile is omitted from the regression and the corresponding cost of repairs is reflected in the constant term.

F. **The number of transactions and the peer-price effect.**

Table F1 splits the results presented in section 5 into areas with different numbers of transactions. Specifically, places where fewer or more than 5 repeated transactions occur during the sample period. This is guided by the theory outlined in section 2 which predicts that the number of transactions has a material effect on how much information can be inferred from prices in the neighbourhood. While the average return of the neighbourhood has a much stronger effect in areas where more transactions occur, it remains highly statistically significant in all locations. Note that the fact that the average price in the neighbourhood has a stronger effect in neighbourhoods where a larger number of transactions occurs is consistent with the assumption that buyers learn from prices of other transactions. The more transactions occur in an area, the more information is contained in average prices and the lower the expected noise of this signal. It is therefore intuitive to place more weight on information form average prices of many transactions than few.

In addition, the reduced form specified in equation 6 predicts that in neighbourhoods with more transactions the impact of a single renovation on the average price in the neighbourhood should be smaller. This is supported by the below results which show that a single renovation in a location where more than 5 transactions occurred has a lower impact on the average price in the neighbourhood than in neighbourhoods with fewer transactions. This is clear in the first stage as additional renovations have a larger effect on average prices in small neighbourhoods. In addition, the results are consistent with the theory as after adjusting the impact of a single renovation for coefficients of the second stage the measured peer-price effect is larger when fewer transactions are aggregated to a peer benchmark.

Table F1. Regression results of the change in house prices as a function of internal renovations of neighbours – instrumenting average prices in small and big neighbourhoods with internal renovations to test the robustness of peer-price estimates (the instrumented variables are in bold).

	I	*II*	*III*	*IV*
	NH<5	***NH<5***	***NH>5***	***NH>5***
Internal renovation	*0.0498****	*0.0534****	*0.0503****	*0.0528****
	(7.12)	*(8.80)*	*(7.53)*	*(8.76)*
Average prices in NH	*0.208****	***0.618*****	*0.587****	***1.157*****
	(18.98)	***(6.48)***	*(31.54)*	***(11.85)***
NN int. ren.	*0.0212**		*0.0302****	
	(2.42)		*(3.43)*	
Instrument		*% of ren.*		*% of ren.*
Time controls	*Yes*	*Yes*	*Yes*	*Yes*
Location controls	*Yes*	*Yes*	*Yes*	*Yes*
N	*14110*	*14110*	*10198*	*10198*
R^2	*0.287*	*0.215*	*0.398*	*0.341*

Notes: t statistics in parentheses, NN stands for the Nearest Neighbour, NH stands for Neighbourhood (100m radius from property i), dummy variables are underlined, all instrumented variables are in bold, significance is denoted at * p<0.05, ** p<0.01, *** p<0.001. Columns I and III present OLS results of a reduced form model with the average return in the neighbourhood. Columns II and IV show 2SLS results where the average return in the area is instrumented with the percentage of properties in the area that have been internally renovated. Columns I and II are for locations where 5 or fewer transactions occur. Columns III and IV are for places where more than 5 transactions occur.

G. **Conditions for the multiplier effect.**

Consider the possible mechanism based on learning from other prices. As demonstrated in the main body of the paper, the price of property i in this case is given by its own unique characteristics x, the average price in the area P_n and the average of the impact of unique features that affect those prices but should have no impact on other transactions $\bar{s}_n$:

$$P_i = \beta x_i - \frac{\alpha\beta}{\alpha+\beta}\bar{s}_n + \frac{\alpha}{\alpha+\beta}P_n$$

This formula has an intuitive interpretation when considering internal renovations: if internal renovations are of type s (affect only the renovated property and have no impact on the fundamentals of other houses), then this internal renovation should affect P_n and $\bar{s}_n$ simultaneously and therefore have no impact on P_i. However, this is only true if information about the internal renovation is public. Perfect information implies no learning through prices. With information frictions, prices contain a signal and there are two options:

a) The signal is perfectly interpreted by the market so that when P_n is affected by the price of a renovated property, the market adjusts $\bar{s}_n$ at the same time. This implies learning through prices but no multiplier effect.
b) The signal is interpreted by the market with an error so that the change in $\bar{s}_n$ is different than in a). This error will compound into subsequent transactions through their cumulative effect on the average price in the area.

There is also a possibility that an internal renovation is of type k (affects other properties directly). With perfect information, there is no learning through prices but with frictions, are also two possibilities:

a) The signal is perfectly interpreted by the market so that when P_n is affected by the price of a renovated property, prices of other properties react to the information revealed and interpreted as an internal renovation. This implies learning through prices but no multiplier effect.

b) The signal is interpreted by the market with an error so that when P_n is affected by the price of a renovated property, other properties do not know what the signal represents and are forced to make assumptions about what it means for their fundamental values. If they do not interpret the signal accurately the change in P_n will be different than in a) and this difference will translate into a multiplier effect.

H. **Summary statistics of neighbourhoods.**

The below table presents socio-economic characteristics of areas included in the study. The data comes from the 2011 census and is only available as a cross section of Census Output Areas. These are defined by ONS based on size and on average include around 15 households. I match them to postcodes based on a mapping tool provided by the Office for National Statistics to obtain neighbourhood level characteristics. The table presents summary statistics for all postcodes in the 15 boroughs of London in the ONS database in which there are no observed repeated transactions (right) against summary statistics for postcodes where there is at least one repeated transaction (left).

Table H1. Summary statistics at postcode level.

	Mean	S.D	Min	Max	Mean	S.D	Min	Max
Residents per hectare	91.15	56.10	0.30	565.80	108.86	289.90	0.30	22600
Very bad health	2.93	2.86	0.00	52.17	2.32	3.17	0.00	88.89
Live as a couple	52.06	11.07	13.60	79.50	41.65	11.22	2.00	81.80
0.5 person per bedroom	38.74	16.71	3.00	139.00	31.74	15.93	0.00	139.00
Share of white population	72.75	17.43	5.70	99.60	65.44	16.70	4.30	99.60
Home ownership rate	60.87	22.41	2.10	100.00	35.43	21.39	0.00	100.00
Educated to L4	40.28	16.47	6.40	85.46	47.02	16.21	5.48	91.72
Work from home	10.17	4.53	0.00	45.00	12.30	6.22	0.00	45.00
Unemployment	4.38	2.39	0.00	19.50	4.67	2.78	0.00	22.50
Number of postcodes	15281				161747			

Notes: data from 2011 census. 'Very bad health' gives the percentage of respondents who reported very bad health. '0.5 person per bedroom' is the share of households with 0.5 people per bedroom on the house or fewer. 'Educated to L4' is the rate of residents with higher education.

The table shows that the postcodes included in the sample represent around 10% of all postcodes with no statistical differences to the rest of the sample.